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(54) A LOW FREQUENCY INDUCTIVE RF PLASMA REACTOR

INDUKTIVER PLASMAREAKTOR IM UNTEREN HOCHFREQUENZBEREICH

REACTEUR A PLASMA HF INDUCTIF A BASSE FREQUENCE

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(73) Proprietor: Mattson Technology Inc.
Fremont, California 94538 (US)

(72) Inventor: Savas, Stephen, E.
Alameda. Valifornia (US)

(74) Representative: Nash, David Allan et al
Haseltine Lake & Co.,
Imperial House,
15-19 Kingsway
London WC2B 6UD (GB)

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Description

Technical Field

This invention relates in general to a wafer processing system and relates more particularly to a wafer processing plasma reactor for processing a semiconductor substrate in which the plasma is generated primarily by inductively coupled power. The invention relates also to a method of processing a semiconductor substrate.

In the figures, the first digit of a reference numeral indicates the first figure in which is presented the element indicated by that reference numeral.

Background Art

Plasma etching or deposition in the fabrication of circuits is attractive because it can be anisotropic, can be chemically selective and can produce processing under conditions far from thermodynamic equilibrium. Anisotropic processing enables the production of integrated circuit features having sidewalls that extend substantially vertically from the edges of a masking layer. This is important in present and future ULSI devices in which the depth of etch and feature size and spacing are all comparable.

In Figure 1 is shown a typical wafer processing plasma reactor 10. This reactor includes a dielectric coated metal wall 11 that encloses a plasma reactor chamber 12. Wall 11 is grounded and functions as one of the plasma electrodes. Gases are supplied to chamber 12 from a gas source 13 and are exhausted by an exhaust system 14 that actively pumps gases out of the reactor to maintain a low pressure suitable for a plasma process. An rf power supply 15 connected to a second (powered) electrode 16 capacitively couples power into a plasma in chamber 12. A wafer 17 is positioned on or near powered electrode 16 for processing. Wafers 17 are transferred into and out of reactor chamber 12 through a port such as slit valve 18.

RF power at 13.56 MHz is predominantly utilized in plasma reactors because this frequency is an ISM (Industry, Scientific, Medical) standard frequency for which the government mandated radiation limits are less stringent than at non-ISM frequencies, particularly those within the communication bands. This substantially universal use of 13.56 MHz is further encouraged by the large amount of equipment available at that frequency because of this ISM standard. Other ISM standard frequencies are at 27.12 and 40.68 MHz, which are first and second order harmonics of the 13.56 MHz ISM standard frequency.

A plasma consists of two qualitatively different regions: a quasineutral, equipotential conductive plasma body 19 and a boundary layer 110 called the plasma sheath. The plasma body consists of substantially equal densities of negative and positive charged particles as well as radicals and stable neutral particles. RF power coupled into the reactor chamber couples energy into the free electrons, imparting sufficient energy to many of these electrons that ions can be produced through collisions of these electrons with gas molecules. The plasma sheath is an electron deficient, poorly conductive region in which the gradient in the space potential (i.e., the electric field strength) is large. The plasma sheath forms between the plasma body and any interface such as the walls and electrodes of the plasma reactor chamber.

When the powered electrode is capacitively coupled to the rf power source, a negative dc component V_{dc} of the voltage at this electrode (i.e., the dc bias) results (see, for example, H.S. Butler and G.S. Kind, **Physics of Fluids**, 6, p. 1348 (1963). This bias is a consequence of the unequal electron and ion mobilities and the inequality of the sheath capacitances at the electrode and wall surfaces. The magnitudes of the sheath capacitances are a function of the plasma density as well as the chamber geometry and the relative areas of the electrode and wall within the plasma chamber. Sheath voltages at the powered electrode on the order of several hundreds of volts are commonly produced (see, for example, J. Coburn and E. Kay, *Positive-ion bombardment of substrates in rf diode glow discharge sputtering*, **J. Appl. Phys.**, 43, p. 4965 (1972)).

The dc component of the sheath potential at the powered electrode is useful in accelerating ions to higher energy in a direction substantially perpendicular to the powered electrode. Therefore, in a plasma etching process, a wafer 17 to be etched is positioned on or slightly above the powered electrode 16 so that this flux of positive ions is incident substantially perpendicular to the plane of the wafer, thereby producing substantially vertical etching of unprotected regions of the wafer. These high sheath voltages (and high discharge voltage) are needed in some processes (like SiO_2 etching) to produce etch rates that are required for a commercial etch process.

Transistor speed specifications and high device densities in the most modern MOS integrated circuits have required the use of shallow junctions and thin (on the order of 10 nm) gate oxides under polysilicon gates that are thousands of Angstroms thick 1Å = 10^{-1} nm. Unfortunately, such IC structures are sensitive to ion bombardment by high energy (> 100 eV) ions such as in the conventional plasma etch apparatus of Figure 1 so that, during the step of etching the polysilicon layer to form the gate, it is difficult to avoid damaging the gate oxide. Because wafer damage decreases with decreasing ion energy and associated sheath voltage, it would be advantageous to operate at smaller discharge power levels and voltages. Unfortunately, for capacitively coupled power at 13.56 MHz, this reduction of voltage results in a proportionately slower etch rate for many processes, which thereby significantly degrades process throughput.

Etch rates for SiO_2 and some Si etch processes are a function of the ion bombardment power density transmitted from the plasma to the wafer. Since this power is equal to the product of the sheath voltage at the powered electrode and the ion current density at the wafer, the ion current density at the wafer must be increased to maintain substantially constant etch rate with decreased sheath voltage. This requires that the plasma ion density near the wafer be increased. Unfortunately, in a conventional plasma etcher, both the sheath voltage of the powered electrode and the ion density near that electrode are proportional to each other and are monotonically increasing functions of the amplitude of the rf voltage applied to the powered electrode. Thus, if the sheath voltage is decreased by decreasing the voltage of the rf signal, then the current density of the ion beam at the wafer also decreases thereby producing an even greater percentage decrease in etch rate than in either the sheath voltage or the ion current. It would therefore be advantageous to be able to control independently the sheath voltage and ion density at the wafer so that a soft etch process (i.e., an etch process with reduced sheath voltage at the wafer) can be implemented that has a commercially adequate etch rate.

One method of increasing etch rate by enhancing plasma ion density near the wafer utilizes magnets to produce a magnetic containment field that traps electrons within the vicinity of the wafer, thereby increasing the ion production rate and associated density at the wafer. The magnetic containment field confines energetic electrons by forcing them to spiral along helical orbits about the magnetic field lines. Unfortunately, nonuniformities of the magnetic containment field of such "magnetically enhanced" plasma etching systems decrease etch rate uniformity over the surface of the wafer. The $\vec{E} \times \vec{B}$ drifts due to the electric field in and near the sheath also reduce etch rate uniformity in such systems. To improve uniformity over the surface of the wafer in one such system, the wafer is rotated about an axis that is perpendicular to and centered over the surface of the powered electrode. This produces at the wafer surface a cylindrically symmetric time-averaged field that has improved average uniformity over the wafer, thereby producing increased etch uniformity. However, this rotation produces within the plasma chamber undesirable mechanical motion that can produce particulates and increase contamination.

Another technology that has potential for producing acceptable etch rates at low ion bombardment energy is the recently developed technique of electron cyclotron resonance plasma production. This technique has application to wafer cleaning, etching and deposition processes. In this technique, a plasma is produced by use of a microwave source and a magnetic containment structure. Unfortunately, this technique, when applied to etching or chemical vapor deposition, exhibits high levels of particulate formation, poor radial etch rate uniformity and low throughput. The fraction of energy coupled into production of radicals increases very rapidly above about 0.13 Pa (1 m Torr) so that the pressure in this system must be kept below this level. This requires expensive hardware that includes: (1) a very large pumping speed (> 3,000 liters per second, which is 10 times typical values) vacuum pumping system to produce the very low (0.013-0.13 Pa or 0.1 - 1 m Torr) pressures required for this process; and (2) a large magnetic containment system that sometimes includes large electromagnets.

Another technique for increasing the ion density utilizes a microwave plasma generator to generate ions in a region at least 10 cm above the wafer. These ions flow into the volume above the wafer and therefore contribute to the ion density at the wafer. However, this approach tends to produce copious amounts of free radicals and produces no more than a few milliamps/cm^2 ion current density at the wafer.

In Josef Freisinger and Horst W. Loeb, *The neutral particles injectors RIG for fusion reactors*, **Atomkernenergie-Kerntechnik, Vol. 44 (1984) No. 1, p. 81-86.** a neutral beam of particles is generated to inject the amount of additional power needed to produce a breakeven point in energy production in a Tokamak fusion reactor. This beam is produced by first producing an ion beam by means of inductively coupled power and then neutralizing the beam by passing it though a gas before entry into the fusion reactor. The ion beam is extracted by a dc field instead of an rf field as in the present application.

In the reactor presented in the article J. Freisinger et al entitled *RF-ion source RIM 10 for material processing* with *reactive gases*, **IX International Conference on Gas Discharges and their Applications, 19-23 September 1988)**, power is inductively coupled into the chamber to heat electrons and an ion beam onto a wafer is produced by a dc field instead of by an rf field.

In U.S. Patent US-A-4,362,632 entitled *Gas Discharge Apparatus*, issued to Adir Jacob on December 7, 1982, a plasma reactor is presented that includes a coil that encircles the reactor and a Faraday shield. A Faraday shield within the reactor prevents the magnetic field produced by the coils from penetrating into the portion of the reactor inside of the cylindrical Faraday shield. Therefore, a plasma is generated only in the region between the wall and the Faraday shield. Because there is no split in this shield, this Faraday shield excludes the time varying electromagnetic fields from the region enclosed by the shield. This is done to prevent the introduction of nonuniformities in plasma density in that region as a result in nonuniformities in the field in that region. Ionized plasma gases diffuse into the region enclosed by the Faraday shield via holes in the Faraday shield.

Also, his shield is not a split Faraday shield and is why it blocks the time-varying magnetic field from penetrating into the inside of the shield. In contrast to this, all of the plasma is produced inside of applicant's split

Faraday shield. The magnetic field penetrates past the split Faraday shield to generate an azimuthal electric field that produces the plasma. Therefore, Jacob does not teach or suggest the structure taught and claimed by applicant.

In the published specification of US Patent No. 4918031 (Johnson et al.), equivalent to published European Patent Application No. EP-A-0376546, there is disclosed a helical resonator for producing a plasma for use in fabricating semiconductors. This resonator employs a discharge tube enclosed by a helical coil through which rf power can be coupled into the plasma produced in the tube, and one form of resonator utilises a split metallic shield for adjusting "plasma species concentrations by application of a bias or to shield the plasma region from radial electric fields." The shield has a single split formed therein.

In a later patent, US Patent No. US-A-52345290, issued to the same inventor, there is further, more informative discussion of the function of this split metallic shield in which it is acknowledged that "the [earlier] patent provides no significant disclosure concerning its details or use."

In this later patent, the applicant makes the further acknowledgement that "It is first noted that the shield shown in the aforementioned patent is not perfect and does allow some capacitive coupling therethrough. The current, generated in a capacitance measurement however, is so low as not to be directly measurable by means available to me. I do know, however, that in an actual experimental shield of the type shown in Figure 2 of the patent, the area of the single vertical slit through the shield is somewhat less than 0.2% of the total external area of the shield."

Additional prior art is also to be found in:

1 "Plasma Physics - Study of the electron temperature and density of an inductive HF discharge in hydrogen, using the symmetrical double-probe method" - report by Mr. Guy Turban, as presented by Mr Louis Nèel. C.R. Acad. Sc. Paris, Vol. 273 (September 27, 1971), Series B, pp 533-536.

2 "Plasma Physics - Measurement of the energy-distribution function of electrons in an inductive HF discharge in hydrogen, using the asymmetric triple-probe method" - report by Mr. Guy Turban, as presented by Mr Louis Nèel, C.R. Acad. Sc. Paris, Vol. 273 (October 4, 1971), Series B, pp 584-587.

3 "The Hundred year History Of Induction Discharges", Hans U. Eckert, Proceedings 2nd Annual International Conference on Plasma Chemistry and Technology, Herman Boenig, Ed, Techromic Publ., Lancaster, PA, 1986 pp 171-201.

4 "ICRH Antenna Design And Coupling Optimization Studies", R.R. Weynants et al., Proceedings of 2nd Joint Grenoble-Vienna International Symposium, Vol. 1 (Como, Italy) 1980.

According to the present invention, there is provided a plasma reactor for processing a semiconductor substrate comprising:

a nonconductive reactor wall enclosing a reactor chamber within which a plasma is to be generated to produce at least one plasma product for processing the semiconductor substrate;
means for connection a gas source and a gas exhaust system to the reactor chamber;
an induction coil for inductively coupling rf power into the reactor chamber from a source of rf power;
a split Faraday shield between the induction coil and the nonconductive reactor wall and providing a plurality of substantially nonconductive gaps such that the source of rf power can couple power through the split Faraday shield to sustain said plasma; and
a support for the semiconductor substrate positioned such that the semiconductor substrate is exposed to the at least one plasma product during processing.

According to a second aspect of the present invention there is provided a method of processing a semiconductor substrate in a plasma reactor comprising the steps of:

supplying gas to a reaction chamber;
shielding the gas in the reaction chamber with a split Faraday shield, the split Faraday shield forming a plurality of substantially nonconductive gaps to allow the passage of inductively coupled power into the gas in the reaction chamber;
inductively coupling power into the gas through said split Faraday shield to sustain a plasma in the reaction chamber;
forming at least one plasma product for processing the semiconductor substrate; and
exposing the semiconductor substrate to said at least one plasma product for processing.

In accordance with the illustrated preferred embodiment, a plasma reactor is present in which low frequency (0.1-6MHz) rf power is inductively coupled into the plasma to provide energy for ionisation of the gas near a wafer-holding, powered electrode and a high frequency voltage of lower power is applied to the powered electrode to control the ion bombardment energy of a water upon this electrode. A wafer is placed on or just above this powered electrode for processing.

This plasma reactor has a nonconductive chamber wall that is encircled by an induction coil that is connected to a low frequency rf source. A split Faraday shield is positioned between the induction coil and the sidewall

of the reactor and encircles the reactor to substantially eliminate the production of displacement currents between the induction coil and the plasma reactor. This shield, in effect, greatly reduces the capacitive coupling of the low frequency rf electric field to the plasma (See, the article by J. L. Vossen, entitled *Glow Discharge Phenomena in Plasma Etching and Plasma Deposition*, J. Electrochem. Soc. Solid-State Science and Technology, Vol. 126, No. 2, February 1979, p. 319) so that the energy of ion bombardment and associated etching and sputtering of the reactor wall is substantially eliminated and so that the modulation of the wafer sheath voltage at the low frequency is reduced.

This Faraday shield is movable so that the capacitance between the plasma and the shield can be varied. The Faraday shield is placed substantially in contact with the chamber outer wall, producing a high value of capacitance during wafer processing. This reduces the rf plasma potential, thereby reducing plasma etching of the walls of the reactor. An increased gap between the Faraday shield and the chamber wall yielding a reduced value of capacitance can be used outside of periods of wafer etching to produce increased rf and time-averaged plasma potential levels, thereby causing higher energies of ion bombardment that permit cleaning of the reactor walls with a controlled level of etching. Preferably, the Faraday shield is moved radially to alter capacitance, but the capacitance could also be varied by vertical movement of the Faraday shield. In an embodiment in which the shield is movable vertically, the shield should not be allowed to move far enough vertically that it does not lie between the reactor chamber and every coil of the induction coil. A conductive sheet can be included above the top of the chamber to increase the capacitance of the plasma to the effective rf ground electrode provided by the reactor wall. This plate can also be movable to vary the capacitance between the plasma body and this portion of the Faraday shield.

A dc magnetic field can be included to enhance ion generation at low pressures by confining electrons away from the walls of the chamber. At low pressure, electrons have an increased mean free path that would increase their rate of loss from the chamber by collisions with the chamber wall. This magnetic field forces the electrons into helical paths that have an increased chance of making ionizing collisions within the chamber before colliding with a wall.

A diverging magnetic field which is stronger near the top of the reactor chamber can be included to reflect electrons back into the plasma, thereby preventing their loss at the top wall of the chamber. This latter magnetic field (which might be as small as several ten-thousandths of a Tesla near the top of the chamber) can be produced either by an array of permanent magnets positioned on top of the chamber and having alternating directions of their magnetic fields, by a solenoidal coil carrying dc current or by a ferromagnetic disk.

The inductively coupled rf power is supplied at a frequency in the range 0.1 - 6 MHz and at a power level up to 10 kW, depending on the size of the reactor chamber. The voltage applied to the powered electrode is at a frequency much higher than the inverse of the average time for an ion to cross the sheath at the powered electrode. Preferred choices for the frequency f_h of this voltage signal are any of the ISM standard frequencies 13.56, 27.12 and 40.68 MHz. The higher frequencies will be needed for higher densities of plasma in order to produce ion bombardment energies which are not too broadly distributed.

The sheath at the powered electrode contains a strong electric field that is substantially perpendicular to the plane of the wafer, thereby producing substantially vertical ion impact and associated substantially vertical or controlled taper etching of the wafer. The amount of capacitively coupled power provided to the powered electrode is substantially less than the power provided inductively to the plasma. Therefore, the average ion current at the wafer is primarily determined by the inductively coupled power and, due to the Faraday shield, the average ion energy at the wafer is substantially a function only of the amplitude of the rf signal to the powered electrode. In contrast to this, in the typical plasma reactor illustrated in Figure 1, both the average ion density (which is typically somewhat lower) and energy are controlled by the amplitude of the rf signal to the powered electrode. The inductively coupled reactor therefore enables the sheath voltage to be reduced and the ion density to be increased. Also, the sheath voltage and ion density can be separately varied. Consequently, a soft etch at a commercially acceptable etch rate can be achieved that does not damage the recent type of integrated circuits that can be damaged by ions of impact energy of order or greater than 100 eV (electron volts).

The electromagnetic fields in the inductively coupled plasma reactor can produce a plasma ion density distribution that is very uniform over the wafer and therefore produces very uniform wafer processing. The inductively generated electric field is substantially circumferential and therefore accelerates electrons substantially parallel to the side wall of the reactor. Because of the conductivity of the plasma, the strength of this electric field decreases rapidly away from the side wall so that electron acceleration occurs primarily in a region near the side wall. As an electron gains speed, its inertia produces a trajectory that may include a succession of elastic collisions with molecules and/or glancing collisions with the sheath at the side wall. Such collisions can kick the electron into the plasma body. This results in significant electron acceleration only near the wall, but also results in ion generation throughout the chamber. The diffusion of these electrons and ions and the radial $\vec{E} \times \vec{B}$ drift of electrons produces near the wafer a radially symmetric ion density that has a very uniform density. A low pressure (typically, on the order of 0.13 - 3.9 Pa (1 - 30 m Torr) is maintained in the reactor chamber to facilitate diffusion of the electrons away from the

region where they gain energy near the side wall.

This design is also extremely efficient in coupling power into the production of ions and therefore provides an important advantage over other reactors for wafer processing that is to be performed by the ions in the plasma (see, for example, the article by J. Freisinger et al entitled *RF-ion source RIM 10 for material processions with reactive gases,* **IX International Conference on Gas Discharges and their Applications, 19-23 September 1988).** The importance of this can be seen from the following. RF power to a plasma produces neutral radicals, ions, free electrons and excitation of molecules and atoms by the free electrons. The vertical etching that is produced by reactive ions is favored in a chamber that channels a high fraction of the rf power into ion production. For excess radical concentrations, the reaction on the wafer surface by the radicals can be detrimental to the desired fabrication process so that it is also advantageous in many applications to reduce the relative production of free radicals by the plasma. Therefore, this plasma reactor is particularly suitable for reactive ion etch processes and other processes that are either favored by high ion concentration or degraded by significant free radical concentration. This reactor also requires much less capacitively coupled power than conventional plasma reactors. This system utilizes on the order of a few hundred Watts of rf power to the powered electrode compared to 500-1000 W (Watts) for a conventional plasma reactor in which all power is coupled capacitively. This system also provides the ability to control independently the ion current and the ion impact energy.

In the conventional plasma reactor of Figure 1, the amplitude of the rf signal applied to powered electrode 16 controls not only the ion density in the plasma, but also the sheath voltage of the powered electrode. To achieve a soft etch (i.e., energy of ion bombardment of the wafer on the order of 100 V (volts) or less) the capacitively applied rf power should be reduced below that conventionally used in such a reactor. Unfortunately, this reduction of capacitively applied power would not only reduce the voltage drop across this sheath, it would also reduce the ion density at this sheath. Even at high rf voltage to the powered electrode, such capacitively coupled power produces only a relatively low density of ions. Because the wafer etch rate is proportional to the product of the ion density at this sheath times the voltage drop across this sheath, the wafer etch rate decreases faster than either of these two parameters. Thus, a soft etch produces a reduction in throughput that is incompatible with a commercial integrated circuit fabrication process.

That the sheath voltage in this system is tied to the amplitude of the rf signal applied to the powered electrode can be seen by reference to Figures 2 and 3. A capacitor 21 between rf source 15 and powered electrode 16 enables this sheath voltage to have a dc component. This dc component is produced by the combined effects of the unequal areas of the electrodes and the unequal mobilities of the electrons and ions. Each plasma sheath is electronically equivalent to the parallel combination of a resistance, a capacitance and a diode. The electric field across the sheath repels most of the electrons out of the sheath region producing a large sheath resistance on the order of $10^4\ \Omega$ (ohms). The capacitive component of the sheath impedance as a function of increasing frequency becomes small enough to be significant at about 500 kHz and can be substantially ignored much below that frequency. At frequencies much above 500 kHz, the sheath resistance is large enough that it can be ignored. This is the case for the high frequency sheath voltage component at the frequency of the capacitively coupled power.

In the equivalent circuit in Figure 2, the effects of the much higher mobility of the electrons than the ions in the plasma and sheath is modeled by diodes 24 and 28. Thus, if the plasma were to become negative with respect to any electrode adjacent to the plasma, the electrons in the plasma would see an effective short to that electrode. The sheath impedances are therefore modeled by elements 22-24 and 26-28. The plasma body can be modeled as a low impedance resistance 25 that can be ignored at the high frequency f_h (preferably one of the ISM frequencies 13.56 MHz, 27.12 MHz or 40.68 MHz) utilized for the rf voltage applied to the powered electrode.

Figure 3 illustrates the relationship between a 220 V (volt) peak-to-peak rf signal 31 of frequency f_h applied to the powered electrode, the resulting voltage 32 of the plasma and the sheath voltage 36 of the powered electrode. The sheath capacitances C_{s1} and C_{s2} dominate at the frequency f_h of the capacitively coupled power so that resistances R_{s1} and R_{s2} can be ignored and diodes 24 and 28 can be ignored except for a short interval during each period of signal 31. Therefore, under most operating conditions, the plasma equivalent circuit reduces to a capacitive divider so that the plasma potential V_p and the high frequency components of the voltages across capacitances C_{s1} and C_{s2} are substantially in phase and related in magnitude by $V_p = V_{rf} C_{s2}/(C_{s1} + C_{s2})$.

For a typical reactor with a wall area several times that of the powered electrode, the sheath capacitance C_{s2} at the wall is on the order of 10 times the sheath capacitance C_{s1} at the powered electrode. Therefore, for a 220 V (volt) peak-to-peak rf signal 31, the plasma potential V_p is on the order of 20 V (volts) peak-to-peak. Because signals 31 and 32 are in phase, a peak 33 of signal 32 is aligned with a peak 34 of signal 31. Because of diode 24, the minimum voltage difference between signals 31 and 32 (occurring at each peak 34) is on the order of kT_e/e. Similarly, V_p must also be at least kT_e/e more positive than ground 35 to avoid shorting the plasma to the walls of the reactor. These various requirements produce an average sheath voltage 36 of the powered electrode (i.e., the dc component of rf signal

31) of approximately -90 V (volts). The dc component of the sheath voltage is substantially equal to $-V_{rf} \cdot C_{s1}/(C_{s1} + C_{s2})/2$ where V_{rf} is the peak-to-peak magnitude of the rf voltage. The sheath voltage varies directly with the magnitude of the rf signal because the electric field component of the rf signal is substantially perpendicular to the powered electrode. This means that the dc component 36 of voltage 31 is directly tied to the peak-to-peak amplitude of the rf voltage applied to the powered electrode.

The ionic current density at the powered electrode of a conventional plasma reactor is proportional to the ion density in the plasma which in turn decreases with decreasing power so that if the rf voltage amplitude is decreased to decrease the sheath voltage, then the current density also decreases. Therefore, the plasma reactor of Figure 1 does not enable the current density at the wafer to be increased to maintain etch power when the voltage is decreased to produce a softer etch.

The voltage drop across the sheath at the powered electrode is equal to the difference between the applied rf signal 31 and the voltage 32 of the plasma. This voltage drop varies from about 0 volts to about -220 V (volts). If an ion were to cross this sheath in a time interval that is short compared to the period $1/f_h$ of the rf signal, then its bombardment energy could be almost zero if it crossed the sheath near a peak 34 of rf signal 31. Such low energy bombardment ions would not necessarily have trajectories substantially perpendicular to the plane of the wafer and therefore could degrade the desired vertical etch of the wafer. It is therefore important for the period $1/f_h$ to be no more than half as large as the average time for an ion to cross this sheath. Since this transit time is on the order of or less than a half microsecond, f_h should be at least 4 MHz. For higher ion densities and low sheath voltage, the period $1/f_h$ can be as small as 0.1 μs or less. Because of the less stringent limitations on ISM frequencies, it is preferred that f_h equal one of the ISM frequencies 13.56 MHz, 27.12 MHz and 40.68 MHz.

Brief Description of Drawings

The details of my invention will be described in connection with the accompanying drawings, in which: Figure 1 illustrates the structure of a typical plasma reactor; Figure 2 is an equivalent circuit for a plasma reactor in which power is capacitively coupled into the reactor chamber; Figure 3 illustrates the relationship between the rf signal applied to the powered electrode, the voltage V_p of the plasma and the sheath voltage V_{dc}; Figure 4 is a side view of the inductively coupled reactor; Figure 5 is a cross-sectional side view of the inductively coupled reactor of Figure 4; Figure 6 is a top view of the reactor of Figure 4; and Figure 7 illustrates the relationship of plasma voltage Vp and the rf voltage applied to the cathode for the case when C_{s1} is much larger than C_{s2}.

Modes for Carrying Out the Invention

In Figure 4 is a plasma reactor 4 that allows independent, controllable variation of the sheath voltage and the ion current density at the wafer. This reactor also produces a very uniform distribution of ion current density and voltage at the wafer and can provide an increased ratio between ion and free radical production rates in the plasma relative to purely capacitive or higher frequency inductive discharges. This system is therefore particularly useful for applications in which an increased ratio of ions to free radicals is advantageous.

On a base 40 is a cylindrical chamber wall 41 that encloses a plasma reactor chamber 50 (shown in Figure 5). Chamber wall 41 is on the order of 7 - 30 cm (centimeters) high and has a lateral diameter that is dependent on the diameter of the wafers that are to be processed. For a 15 cm diameter wafer processing system, this chamber wall has a lateral diameter on the order of 25 - 30 cm (centimeters) and for a 20 cm (centimeter) diameter wafer processing system, this chamber has a lateral diameter on the order of 30 - 38 cm (centimeters). Chamber wall 41 is made of a nonconductive material such as quartz or alumina.

Encircling wall 41 is an inductive coil 42 that is connected to a first rf source 43 through a conventional impedance match network or transformer 44. This coil has only a few turns (on the order of 2-8 turns) to produce an inductance that can be conveniently matched to rf source 43 by a conventional match network 44 utilizing commercially convenient reactance values or by a transformer to match the inductive impedance (typically, equal to or less than 10 ohms) to the impedance (typically, 50 Ω (ohms)) of source 43. The match network is designed to substantially eliminate the reflection of power back to source 43. This inductive coil produces within chamber 50 an axially symmetric rf magnetic field whose axis is substantially vertical and an electric field that is substantially circumferential. Both of these fields exhibit a rotational symmetry about a central axis A. This rotational symmetry contributes to the uniformity of wafer processing.

Because of the high conductivity of the plasma, the inductively coupled fields are substantially limited to a region adjacent to the side wall of skin depth 6 (on the order of a centimeter) proportional to the square root of the electron density in the plasma divided by the frequency f_1 of the inductively coupled rf field. For larger systems, f_1 can be reduced to increase the thickness of this region within which electrons are accelerated.

Within this region, the circumferential electric field accelerates the electrons circumferentially. However, because of the inertia of these accelerated electrons, they may experience glancing collisions with the electric field of the sheath at the sidewall. Such collisions will reflect most of these electrons away from the wall. Some of these electrons will strike the side wall and may produce secondary electrons. Elastic collisions with gas

molecules cause the electrons to diffuse throughout the volume of the chamber. Because the inductively generated electric field is limited to the distance δ (the resistive skin depth) from the side wall, electron heating is limited to this region. In order to enhance the uniformity of ion density across the wafer, the pressure is kept low (typically 0.13 - 3.9 Pa or 1-30 m Torr) so that the electrons heated near the wall can rapidly diffuse away from the wall to produce a very uniform ionization and resulting ion density across the wafer surface.

The reactor radius R, the frequency f_1 and the power of the inductively coupled power are selected to produce a circumferential electric field having a peak-to-peak amplitude on the order of 1 - 10 V/cm (volts/cm). This results in an oscillatory electron path of amplitude on the order of or greater than 3 cm so that the mean free path of these electrons is on the order of or less than the amplitude of their oscillatory motion. Source 43 provides power at a frequency in the range 0.1 - 6 MHz and at a power of up to 10 kW.

A second rf source 51 (shown in Figure 5) provides rf power to a powered electrode 52, preferably at one of the ISM (Industry, Scientific, Medical) standard frequencies (i.e., 13.56 MHz, 27.12 MHz or 40.68 MHz). As in the embodiment of Figure 1, this rf power produces a dc sheath voltage next to the powered electrode 52. The power level is in the range from less than 100W (Watts) to a few (up to 5) hundred W so that the effect of this capacitively coupled rf signal on the ion density is much less than the effect of the power inductively coupled from source 43. This power level is somewhat less than that typically provided to the powered electrode in a plasma reactor. This power level can be kept low to produce a soft (i.e., kinetic energy less than 100 eV) bombardment of the wafer by ions. This low power level to the powered electrode also means that the ion density is determined primarily by the rf source 43. This is advantageous in decoupling control of the ion density and the sheath voltage.

The circumferential direction of the inductively generated electric field makes this field parallel to the powered electrode so that a path integral from the plasma body to the powered electrode along a normal to the powered electrode is zero. As a result of this, unlike in the plasma reactor of Figure 1, there is no rf component across the sheath producing an rf time varying potential difference between the plasma body and the powered electrode. This substantially eliminates coupling of the low frequency induced rf field to the potential of the powered electrode. Therefore, the sheath voltage of powered electrode 52 is determined only by rf source 51.

Enclosing the sidewall of the reactor is a grounded Faraday shield 45 consisting in this embodiment of a dozen symmetrically-arranged conductive plates 46 that conform to the sidewall. Each Faraday shield conductive plate 46 is spaced from its neighboring plates by gaps 48. These gaps are needed to enable the induction rf magnetic field to penetrate within reactor chamber 50. At least one gap is needed to prevent the formation of a circumferential current in the Faraday shield. By Lenz's Law, such a circumferential current would strongly oppose variation of magnetic field within reactor chamber 50, thereby substantially countering the desired action on reactor chamber 50 of the current in coils 42.

This Faraday shield also provides the same functions as the grounded conductive walls of the reactor of Figure 1 -- namely, it confines the capacitively coupled rf fields to the reactor chamber 50 so that they do not stray outside of the chamber and interfere with other equipment or violate federal radiation standards. This shield also provides a return path for the high frequency current from the electrode produced by capacitively coupled power supply 51.

Faraday shield 45 can, when positioned next to the reactor wall, significantly reduce the amount of time variation of the plasma potential V_p at the rf frequency f_1 of source 43. This is important in decoupling the effects of the first rf source 43 and the second rf source 51 on the ion density and the average sheath voltage V_{dc}. At the power levels applied to coils 42, the large inductance (on the order of 1-100 μH (microHenrys)) of these coils produces a large voltage at one or both ends of these coils. If the Faraday shield were absent, then the high voltage end 47 of coil 42 would couple capacitively to the plasma body and impress an rf variation of V_p at the frequency f_1 of source 43 (see, for example, J.L. Vossen, *Glow Discharge Phenomena in Plasma Etching and Plasma Deposition*, **J. Electrochem. Soc.: Solid-State Science And Technology**, Vol. 126, No. 2, p. 319).

The widths of gaps 48 are less than the minimum spacing between these plates 46 and coils 42 so that coils 42 do not significantly couple capacitively through these gaps to the plasma body (see the Vossen reference). If such capacitive coupling to the plasma body were not blocked, this rf variation of V_p would show up as a variation of the sheath voltages (and hence, ion energy) at this same frequency. Furthermore, this electric field could degrade the symmetry of the etch if it were not substantially excluded by the Faraday shield.

Faraday shield 45 also significantly influences the value of the sheath capacitance C_{s2} for the plasma sheath adjacent to the wall 41 of the plasma reactor. If this Faraday shield were not present, then the effective ground for the capacitively coupled rf signal would be provided by the rf induction coil or the environment surrounding the reactor chamber and therefore would be dependent on what other objects were near the reactor. Furthermore, these objects would generally be at a distance that is large enough that the effective ground could be treated as being at infinity. This makes C_{s2} for the side and top walls more on the order of or less than one tenth of C_{s1} instead of ten times C_{s1} as was the case for Figure 3. The result is that the relationship between the plasma potential V_p and the rf signal is more like that

shown in Figure 7 than like that shown in Figure 3.

In Figure 7, it is again assumed that the rf voltage (signal 71) has a peak-to-peak amplitude of 220 volts. For C_{s1} equal to ten times C_{s2}, the plasma voltage signal 72 has a peak-to-peak amplitude of 200 V (volts). The peaks 73 of the plasma voltage V_p again align with the peaks 74 of the rf voltage signal 71 and the spacing between these peaks is again up to several times kT_e/e. Likewise, the spacing of the troughs of V_p from ground is on the order of kT_e/e (which is typically a few volts). The plasma voltage signal 72 therefore has a dc component 76 on the order of 100 V (volts). This contrasts with Figure 3 where the plasma voltage signal 32 has a dc component on the order of 10 V (volts) plus an offset of order kT_e/e.

This greatly increased dc component between the wall and the plasma body results in an unacceptable level of etching or sputtering of the wall by ions in the plasma. Such action not only damages the chamber wall, but also uses up reactant gas and can inject into the plasma contaminants that can interfere with the wafer fabrication processes in the reactor chamber. However, with the Faraday shield 45 closely spaced from wall 41, the effective ground electrode capacitance is increased and C_{s2} is again several times larger than C_{s1} so that the relationship between the rf signal and the plasma voltage V_p is like Figure 3 instead of like Figure 7. Indeed, normally, the spacing between the "plates" (i.e., the plasma and the conductive wall) of the capacitance C_{s2} is on the order of 0.1 cm. For the reactor of Figure 4, when the Faraday shield is closely spaced from wall 41, the capacitance C_{s2} is increased by the thickness of wall 41 divided by the dielectric constant (which is > 4), which is equivalent to a vacuum gap of 0.075 cm. Therefore, the wall capacitance C_{s2} is a little more than half of what it would be for a reactor of the type shown in Figure 1 of comparable dimensions to that in Figure 4.

Plates 46 are movable radially on the order of or more than 1 cm so that capacitance C_{s2} can be substantially decreased by moving plates 46 away from the walls to vary the ratio C_{s1}/C_{s2} over a range on the order of from 0.1 to 10. These plates are moved close to wall 41 during wafer processing so that etching of the chamber wall and the associated production of contaminants are minimized. In periods other than wafer processing periods, the plates can be moved away from the wall by as much as a cm or more to provide a controlled period of etching of the wall to clean the wall. The remnants of this chamber cleaning step are then drawn out of the reactor before further wafer processing is implemented.

Figures 5 and 6 are respectively side cross-sectional and top views of reactor 40 illustrating further optional features of this reactor. Just outside of the top of reactor chamber 50 is a grounded conductive plate 53 that provides for the top of reactor chamber 50 substantially the same function as Faraday shield 45 provides for the sides of this chamber.

On top of the reactor chamber are a set of magnets 54 that alternately orient their North poles downward. A ferromagnetic return plate 55 helps return the flux of the fields produced by the two outermost magnets. The magnets preferably are permanent magnets since this type of magnet economically provides a sufficient magnetic field. This arrangement produces at the top of chamber 50 an array of alternating direction magnetic fields of about 0.01 T (100 Gauss) that act like magnetic mirrors to reflect electrons back toward the plasma body. The fields from these magnets penetrate into the reactor chamber a distance on the order of twice the spacing (on the order of 2-3 cm) between these magnets. In other embodiments, this linear array of magnets could be replaced by a set of concentric ring magnets, again having North poles of successive magnets oppositely oriented vertically. In still other embodiments, a flat disc of ferromagnetic material having its North pole oriented vertically or a single ring dc solenoid could be used to produce a single magnetic mirror, which may have a magnetic field as low as several ten-thousandths of a Tesla near the top of the chamber. The embodiment utilizing a magnetic disc is preferred because it is simple, inexpensive and preserves radial symmetry of the reactor. In contrast to this, the lack of radial symmetry of the magnetic fields from the magnets 54 in Figure 5 will slightly degrade the radial symmetry of wafer etch.

Just outside of the base or top of reactor wall 41 is a conductive coil 56 connected to a dc current source 57 to produce an optional dc magnetic field to further contain electrons away from the side wall. The magnitude of the magnetic field from this coil can be on the order of 0.0001-0.01 Tesla (1-100 Gauss).

The plasma reactor of Figures 4-6 provides significantly improved operation compared to many other existing reactors. Whereas the plasma reactor (discussed in the Background of the Invention) that utilizes a microwave source produces only a few milliamps/cm^2 current density, this reactor could produce up to 50-100 milliamps/cm^2. Tests show that this high current results for a variety of reactant gases, such as SF_6, CF_2Cl_2, O_2 and argon. This indicates that relatively more of the power is going into the production of ions instead of into the production of neutral fragments as in other plasma production methods at pressures above 1 mTorr. These neutral fragments would not contribute to this current. This is important because only the ions are given the perpendicular direction of impact on the wafer that results in the formation of substantially vertical walls. The ability to produce a very low sheath voltage at the wafer means that a 400 nm (4000 Å) thick gate of polysilicon can be etched vertically without damage to or etching of an underlying 10 nm (100 Å) thick SiO_2 gate insulator by reducing the sheath voltage to less than 20-30 V (volts).

Reactor 40 includes a gas source 49 and an exhaust port 58 that is part of an exhaust system 59 that includes a pump to exhaust plasma process products and to keep the pressure to a selected level. Typically,

the pressure is held at on the order of 0.13 - 3.9 Pascal (1 - 30 m Torr) pressure to enhance diffusion of electrons from the electron heating region near the side wall into the bulk volume. Even at this pressure, the inductively coupled power is primarily coupled into production of ions. In contrast to this, other plasma systems such as the microwave plasma systems produce relatively more free radicals at pressures above approximately 0.13 Pa (1-30 m Torr). If a microwave plasma reactor is to primarily produce ions, then the pressure needs to be on the order of or less than a few hundredths of a Pascal. This requires that reactor pumps have speeds greater than a few Torr-liters per second. This large rate of pumping requires either the use of cryogenic pumps closely coupled to the reactor chamber or very large turbo pumps with large ports to the chamber. In contrast, the reactor disclosed herein can operate at higher pressures and requires a pump speed only on the order of a few tens of Pascal-liters per second. This is easily achieved with smaller pumps which need not clutter the space around the chamber and interfere with wafer handling or other essential chamber peripherals. Such pumps also would not require regeneration or pose a safety hazard as do cryogenic pumps.

In Figure 8, there is shown a further plasma reactor according to the present invention which is substantially similar to that shown in Figures 5 and 6 save for the presence of the magnets 54, the conductive plate 53 and the ferromagnetic return plate 55 of the embodiment shown in Figures 5 and 6, and the provision in the Figure 8 embodiment of a gas inlet at the axis of symmetry of the chamber of the reactor. In Figure 8, the reference numerals, preceded by the number '8', used therein designate the equivalent components to those indicated in Figure 5 and which are preceded by the number '4' or '5' as the case may be.

Reference Numerals

10	plasma reactor
11	reactor wall
12	plasma reactor chamber
13	gas source
14	exhaust system
15	rf power supply
16	powered electrode
17	wafer
18	slit valve
19	plasma body
110	boundary layer
21	capacitor
22-24	elements modeling sheath impedance
25	plasma body resistance
26-28	elements modeling sheath impedance
31	rf signal
32	plasma voltage
33	peak of signal 32
34	peak of signal 31
35	ground
36	sheath voltage of the powered electrode
40	base
41	chamber wall
42	inductive coil
43	1st rf source
44	match network
45	Faraday shield
46	conductive plates of Faraday shield
47	high voltage end of coild 42
48	gaps between Faraday shield plates
49	gas source
50	plamsa reactor chamber
51	2nd rf source
52	powered electrode
53	grounded conductive plate
54	magnets
55	ferromagnetic return plate
56	conductive coil
57	dc current source
58	exhaust port
59	exhaust system

Claims

1. A plasma reactor for processing a semiconductor substrate comprising:

   a nonconductive reactor wall (41) enclosing a reactor chamber (50) within which a plasma is to be generated to produce at least one plasma product for precessing the semiconductor substrate;
   means for connection a gas source (49) and a gas exhaust system (59) to the reactor chamber;
   an induction coil (42) for inductively coupling rf power into the reactor chamber from a source of rf power;
   a split Faraday shield (46) between the induction coil and the nonconductive reactor wall and providing a plurality of substantially nonconductive gaps such that the source of rf power can couple power through the split Faraday shield to sustain said plasma; and
   a support for the semiconductor substrate positioned such that the semiconductor substrate is exposed to the at least one plasma product during processing.

2. A plasma reactor as in claim 1 wherein the source of rf power comprises a first source (43) of radio frequency power, and a second source (51) of radio

frequency power.

3. A plasma reactor as in claim 2 wherein the induction coil (42) is coupled to the first source of rf power to inductively couple power into the plasma from the first source; and the reactor further comprises an electrode (52), coupled to the second source of radio frequency (rf) power and on or adjacent to which a semiconductor substrate is to be placed for processing.

4. A plasma reactor as in claim 3 wherein the induction coil (42) encircles the nonconductive reactor wall.

5. A plasma reactor as in either one of claims 3 and 4 wherein the electrode (52) provides the support for the semiconductor substrate coupled to the reactor chamber such that the semiconductor substrate is exposed to the at least one plasma product during processing.

6. A plasma reactor as in any one of claims 1 to 3 wherein the source of rf power (43) provides capacitive and inductive power; and the split Faraday shield is arranged for substantially blocking the capacitive power from the source from reaching the reactor chamber while permitting the inductive power from the source to reach the reactor chamber.

7. A plasma reactor as in claim 1 wherein said split Faraday shield (45) has plates (46) that are movable to vary the capacitance between a plasma body within the reactor chamber and said split Faraday shield.

8. A plasma reactor as in claim 1 wherein said split Faraday-shield (45) comprises a plurality of conductive plates (46) adjacent to said reactor wall, each plate being spaced from a neighbouring plate by a gap (48) that is smaller than the distance between said induction coil and the reactor wall.

9. A plasma reactor as in claim 1 further comprising a powered electrode (52) providing a support, adjacent to which a semiconductor substrate is to be placed for processing, said powered electrode being capacitively coupled to the source (43) of rf power.

10. A plasma reactor as in claim 9 wherein said induction coil (42) produces within the reactor chamber a magnetic field that is substantially perpendicular to said powered electrode, whereby an electric field induced by time variation of the signal to said induction coil is substantially parallel to said powered electrode (52) so that the induced electric field does not directly affect the potentials of the plasma and the powered electrode.

11. A plasma reactor as in claim 9 wherein said source of rf power provides much less power to the powered electrode (52) than to the induction coil, whereby a plasma produced in said reactor chamber has an ion density that is substantially determined by the power to said induction coil.

12. A plasma reactor as in claim 11 wherein the power to the powered electrode has a peak-to-peak voltage amplitude less than 200v (volts) peak-to-peak, whereby this reactor is suitable for a soft etch of a wafer.

13. A plasma reactor as in claim 9 wherein said plates (46) are movable over a distance such that a ratio (C_{s1}/C_{s2}) can be varied over a range that includes the value 1, where C_{s2} is the sheath capacitance between a plasma body and the reactor wall and where C_{s1} is the sheath capacitance between the plasma body and the powered electrode.

14. A plasma reactor as in claim 1 wherein the inductively coupled power is at a frequency f_1 in the range of from 0.1 - 6 MHz.

15. A plasma reactor as in claim 9 wherein the inductively coupled power is at a frequency f_1 and the capacitively coupled power is at a frequency f_h that is at least twice as large as the inverse of an average transit time for an ion to cross a plasma sheath at said electrode.

16. A plasma reactor as in claim 9 wherein the capacitively coupled power is at a frequency f_h that is selected from the set consisting of 13.56 MHz, 27.12 MHz and 40.68 MHz.

17. A plasma reactor as in claim 1 wherein the exhaust system (59) and the gas source (49) cooperatively produce within said chamber (50) a pressure for which ions are produced in said plasma at a rate at least on the order of that at which free radicals are produced.

18. A plasma rector as in claim 1 further comprising a grounded conductive plate (53) adjacent to a top portion of the reactor wall.

19. A plasma reactor as in claim 1 further comprising a source (54) of a dc magnetic field adjacent to a top portion of the reactor wall, thereby helping constrain energetic electrons away from the top portion of the reactor wall.

20. A plasma reactor as in claim 19 wherein said source (54) of a dc magnetic field adjacent to a top portion of the reactor wall comprises a plurality of permanent bar magnets (54) arranged parallel to one an-

other and to the top portion of the reactor wall, each magnet having its North pole oriented substantially perpendicular to a top portion of the reactor wall and having its North pole substantially oppositely directed from any nearest neighbour magnets.

21. A plasma reactor as in claim 20 further comprising: a ferromagnetic return plate (55) which at least covers the magnets (54) on top and provides a ferromagnetic return for magnetic field lines at the outer edges of the plurality of bar magnets.

22. A plasma reactor as in claim 19 wherein said source (54) of a dc magnetic field adjacent to a top portion of the reactor comprises a plurality of concentric annular magnets parallel to the top portion of the reactor wall, each magnet having its North pole oriented substantially perpendicular to the top portion of the reactor wall and oppositely directed from any nearest neighbour magnets; and a ferromagnetic return plate (55) which at least covers the magnets on top and provides a ferromagnetic return for magnetic field lines at the outer edges of the plurality of bar magnets.

23. A plasma reactor as in claim 19 wherein said source (54) of a dc magnetic field adjacent to a top portion of the reactor wall comprises a disk magnet having its North pole oriented substantially perpendicular to the top portion of the reactor wall.

24. A plasma reactor as in claim 19 wherein said source (54) of a dc magnetic field adjacent to a top portion of the reactor wall comprises a dc electromagnet producing a magnetic field having its North pole oriented substantially perpendicular to the top portion of the reactor wall.

25. A plasma reactor as in claim 19 further comprising a dc power source (57), and a coil (56) encircling the reactor and connected to the dc power source to produce a dc magnetic field that is substantially perpendicular to said powered electrode.

26. A plasma reactor as in any one of the preceding claims wherein said plurality of substantially nonconductive gaps is arranged symmetrically about said reactor.

27. A plasma reactor as in any one of the preceding claims wherein said split Faraday shield is radio frequency grounded relative to said induction coil.

28. A plasma reactor as in any one of the preceding claims wherein said split Faraday shield is direct current grounded relative to said induction coil.

29. A plasma reactor as in any one of the preceding claims wherein said split Faraday shield shares a common ground with said first source of radio frequency power.

30. A plasma reactor as in any one of the preceding claims wherein said split Faraday shield is grounded relative to said induction coil.

31. A plasma reactor as in any one of the preceding claims wherein the induction coil produces a magnetic field having a direction and the gaps formed by said split Faraday shield are substantially parallel to the direction of the magnetic field such that the gaps substantially prevent the inducement of a current in the split Faraday shield by said magnetic field.

32. A plasma reactor as in any one of the preceding claims wherein said induction coil has a first end and a second end and wherein said first end is connected to said source of rf power and wherein said second end is connected to a common ground with said source of rf power.

33. A plasma reactor as in claim 32 wherein current is driven through said induction coil between said first end and a second end such that the induction coil inductively couples power from said source of rf power into said plasma.

34. A plasma reactor as in any one of the preceding claims wherein said split Faraday shield forms at least twelve substantially nonconductive gaps which allow said induction coil to couple power into said plasma.

35. A plasma reactor as in any one of the preceding claims wherein the width of said gaps is smaller than the distance between said induction coil and the reactor wall.

36. A plasma reactor as in claim 35 wherein the area of the split Faraday shield and a distance between the split Faraday shield and the plasma are selected such that the capacitive impedance between the plasma and the split Faraday shield is less than the capacitive impedance between the plasma and any source of radio frequency power.

37. A plasma reactor as in claim 35 further comprising at least one source of capacitively coupled radio frequency power; wherein the area of the split Faraday shield and a distance between the split Faraday shield and the plasma are selected such that the capacitive impedance between the plasma and the split Faraday shield is less than the capacitive impedance between the plasma and the or each source of capacitively coupled radio frequency

power.

38. A plasma reactor as in claim 37 wherein the capacitive impedance between the plasma and the split Faraday shield is several times less than the capacitive impedance between the plasma and the or each source of capacitively coupled radio frequency power.

39. A plasma reactor as in claim 1 further comprising a source of capacitively coupled power for said plasma, wherein the source of capacitively coupled power acts as an effective cathode relative to the plasma, the split Faraday shield acts as an effective anode relative to the plasma, and the area of the effective anode is much greater than the area of the effective cathode such that the ratio C_{s2}/C_{s1} is at least 10, wherein C_{s2} is the capacitance between the plasma and the effective anode and C_{s1} is the capacitance between the plasma and the effective cathode.

40. A plasma reactor as in claim 1 wherein an average direct current potential of the plasma is no greater than 30 V (volts) relative to the semiconductor substrate.

41. A plasma reactor as in claim 1 wherein the plasma has a potential modulation no greater than 20 V (volts) peak-to-peak.

42. A plasma reactor as in claim 1 wherein the plasma has a potential modulation on the order of 20 V (volts) peak-to-peak.

43. A plasma reactor as in claim 1 wherein the reactor chamber has a radius, the first source of radio frequency power has a frequency and a power, and the radius of the reactor chamber, and the frequency and the power of the first source of radio frequency power are selected to produce an electric field within the reactor chamber having a peak-to-peak amplitude on the order of 10 V/cm (volts/cm).

44. A plasma reactor as in claim 1 wherein the split Faraday shield is grounded.

45. A plasma rector as in claim 1 wherein each of the substantially nonconductive gaps has a width on the order of 1 cm.

46. A plasma reactor as in claim 1 further comprising means for accelerating charged particles toward the semiconductor wafer.

47. A plasma reactor as in claim 1 further comprising means for varying the capacitance between said shield means the plasma.

48. A plasma reactor as in any one of claims 1 to 47 wherein the semiconductor substrate includes a surface layer of polysilicon and a thin underlying layer of silicon oxide insulator the induction coil couples sufficient power into the plasma to produce a high ion density in the plasma, and the split Faraday shield substantially reduces the level of capacitive modulation that would be present in the absence of the split Faraday shield such that ions from the plasma controllably etch the polysilicon at a high rate without substantially damaging the thin underlying layer of oxide insulator.

49. A method of processing a semiconductor substrate in a plasma reactor comprising the steps of:

supplying gas to a reaction chamber;
shielding the gas in the reaction chamber with a split Faraday shield, the split Faraday shield forming a plurality of substantially nonconductive gaps to allow the passage of inductively coupled power into the gas in the reaction chamber;
inductively coupling power into the gas through said split Faraday shield to sustain a plasma in the reaction chamber;
forming at least one plasma product for processing the semiconductor substrate; and
exposing the semiconductor substrate to said at least one plasma product for processing.

50. A method as in claim 49 further comprising the step of adjusting the spacing of the split Faraday shield from the plasma.

51. A method as in claim 49 further comprising the step of capacitively coupling power into the reaction chamber.

52. A method as in claim 49 wherein the step of forming the at least one plasma product further comprises the step of forming a plasma having an average direct current potential no greater than 30 V (volts) relative to the substrate.

53. A method as in claim 49 wherein the step of forming the at least one plasma product further comprises the steps of forming a plasma having a potential, and maintaining the potential of the plasma such that a modulation of the plasma potential is no greater than 20V (volts) peak-to-peak.

54. A method as in claim 49 further comprising the steps of forming a plasma in the reaction chamber, capacitively coupling power into the plasma through a capacitance C_{s1}, and capacitively coupling power from the plasm to ground through a capacitance C_{s2} between the plasma and the split Faraday shield,

wherein the capacitance C_{s1} is less than the capacitance C_{s2}.

55. A method as in claim 49 further comprising the step of varying the capacitance between the split Faraday shield and the plasma.

56. A method as in claim 49 further comprising the step of varying the capacitance between the split Faraday shield and the plasma relative to the capacitance between the workpiece and the plasma.

57. A method as in any one of claims 49 to 56 wherein the semiconductor substrate includes a surface layer of polysilicon and a thin underlying layer of oxide insulator; the step of exposing the semiconductor substrate to said at least one plasma product further comprises the step of etching the surface layer of polysilicon using the at least one plasma product, and the step of shielding the gas further comprises the step of controlling the energy of the at least one plasma product such that the surface layer of polysilicon is etched without substantially damaging the thin underlying layer of oxide insulator.

Patentansprüche

1. Plasmareaktor zur Bearbeitung eines Halbleitersubstrats, aufweisend:

   eine nicht leitende Reaktorwand (41), die eine Reaktorkammer (50) umschließt, in der ein Plasma erzeugt werden soll, um wenigstens ein Plasmaprodukt zur Bearbeitung des Halbleitersubstrats zu erzeugen,
   eine Einrichtung zur Verbindung einer Gasquelle (49) und eines Gas-Ablaßsystems (59) mit der Reaktorkammer,
   eine Induktionsspule (42) zur induktiven Einkopplung von HF-Energie von einer HF-Energiequelle in die Reaktorkammer,
   eine unterteilte Faraday-Abschirmung (46) zwischen der Induktionsspule und der nicht leitenden Reaktorwand, die mehrere im wesentlichen nicht leitende Spalte bereitstellt,
   so daß die HF-Energiequelle die Energie durch die unterteilte Faraday-Abschirmung zum Aufrechterhalten des Plasmas einkoppeln kann, und
   einen Träger für das Halbleitersubstrat, der so angeordnet ist, daß das Halbleitersubstrat während der Bearbeitung dem wenigstens einen Plasmaprodukt ausgesetzt ist.

2. Plasmareaktor nach Anspruch 1, bei dem die HF-Energiequelle eine erste Quelle (43) einer Hochfrequenz-Energie und eine zweite Quelle (51) einer Hochfrequenz-Energie aufweist.

3. Plasmareaktor nach Anspruch 2, bei dem die Induktionsspule (42) mit der ersten HF-Energiequelle gekoppelt ist, um Energie von der ersten Quelle aus induktiv in das Plasma zu koppeln, und der Reaktor weiterhin eine Elektrode (52) aufweist, die mit der zweiten HF-Energiequelle verbunden ist und an der oder in deren Nähe ein Halbleitersubstrat zur Bearbeitung anbringbar ist.

4. Plasmareaktor nach Anspruch 3, bei der die Induktionsspule (42) die nicht leitende Reaktorwand umgibt.

5. Plasmareaktor nach Anspruch 3 oder 4, bei dem die Elektrode (52) den Träger für das Halbleitersubstrat darstellt, der mit der Reaktorkammer verbunden ist, so daß das Halbleitersubstrat während der Bearbeitung dem wenigstens einen Plasmaprodukt ausgesetzt ist.

6. Plasmareaktor nach einem der Ansprüche 1 bis 3, bei dem die HF-Energiequelle (43) eine kapazitive und eine induktive Energie bereitstellt, und die unterteilte Faraday-Abschirmung so angeordnet ist, daß sie die kapazitive Energie von der Quelle abblockt, so daß sie die Reaktorkammer nicht erreicht, während sie die induktive Energie von der Quelle zu der Reaktorkammer hin durchläßt.

7. Plasmareaktor nach Anspruch 1, bei dem die unterteilte Faraday-Abschirmung (45) Platten (46) aufweist, die bewegbar sind, um die Kapazität zwischen einem Plasmakörper innerhalb der Reaktorkammer und der unterteilten Faraday-Abschirmung zu verändern.

8. Plasmareaktor nach Anspruch 1, bei dem die unterteilte Faraday-Abschirmung (45) mehrere leitende Platten (46) in der Nähe der Reaktorwand aufweist, wobei jede Platte von einer benachbarten Platte durch einen Spalt (48) beabstandet ist, der geringer ist, als der Abstand zwischen der Induktionsspule und der Reaktorwand.

9. Plasmareaktor nach Anspruch 1, weiterhin aufweisend eine mit Energie versorgte Elektrode (52), die einen Träger darstellt, in dessen Nähe ein Halbleitersubstrat zur Bearbeitung angebracht werden kann, wobei die mit Energie versorgte Elektrode kapazitiv mit der HF-Energiequelle (43) gekoppelt ist.

10. Plasmareaktor nach Anspruch 9, bei dem die Induktionsspule (42) innerhalb der Reaktorkammer ein Magnetfeld erzeugt, das im wesentlichen senkrecht zu der mit Energie versorgten Elektrode steht, wobei ein durch eine zeitliche Veränderung des Si-

gnals zu der Induktionsspule induziertes elektrisches Feld im wesentlichen parallel zu der mit Energie versorgten Elektrode (52) steht, so daß das induzierte elektrische Feld nicht direkt die Potentiale des Plasmas und der mit Energie versorgten Elektrode beeinflußt.

11. Plasmareaktor nach Anspruch 9, bei dem die HF-Energiequelle wesentlich weniger Energie zu der mit Energie versorgten Elektrode (52) als zu der Induktionsspule gibt, wobei ein in der Reaktorkammer erzeugtes Plasma eine Ionendichte aufweist, die im wesentlichen durch die zu der Induktionsspule gegebene Energie bestimmt wird.

12. Plasmareaktor nach Anspruch 11, bei dem die Energie für die mit Energie versorgten Elektrode eine Spannungsamplitude von Spitze zu Spitze von weniger als 200 V (Volt) aufweist, wobei dieser Reaktor für ein Weichätzen eines Wafers geeignet ist.

13. Plasmareaktor nach Anspruch 9, bei dem die Platten (46) über einen Abstand bewegbar sind, so daß ein Verhältnis (C_{s1} / C_{s2}) über einen Bereich variiert werden kann, der den Wert 1 enthält, wobei C_{s1} die Hüllkapazität zwischen einem Plasmakörper und der Reaktorwand ist, und wobei C_{s1} die Hüllkapazität zwischen dem Plasmakörper und der mit Energie versorgten Elektrode ist.

14. Plasmareaktor nach Anspruch 1, bei dem die induktiv eingekoppelte Energie bei einer Frequenz f_1 in dem Bereich zwischen 0,1 bis 6 MHz vorliegt.

15. Plasmareaktor nach Anspruch 9, bei dem die induktiv eingekoppelte Energie bei einer Frequenz f_1 und die kapazitiv eingekoppelte Leistung bei einer Frequenz f_h vorliegt, die doppelt so groß ist wie der reziproke Wert einer mittleren Transitzeit für ein Ion zum Durchqueren einer Plasmahülle an der Elektrode.

16. Plasmareaktor nach Anspruch 9, bei dem die kapazitiv eingekoppelte Energie bei einer Frequenz f_h vorliegt, die aus einer der Frequenzen von 13,56 MHz, 27,12 MHz und 40,68 MHz gewählt ist.

17. Plasmareaktor nach Anspruch 1, bei dem das Ablaßsystem (59) und die Gasquelle (49) in ihrer Zusammenwirkung innerhalb der Kammer (50) einen Druck erzeugen, bei dem Ionen in dem Plasma mit einer Rate erzeugt werden, die wenigstens in der Größenordnung liegt, mit der freie Radikale erzeugt werden.

18. Plasmareaktor nach Anspruch 1, weiterhin aufweisend eine geerdete leitende Platte (53) in der Nähe eines oberen Abschnitts der Reaktorwand.

19. Plasmareaktor nach Anspruch 1, weiterhin aufweisend eine Quelle (54) eines Gleich(DC)-Magnetfelds in der Nähe eines oberen Abschnitts der Reaktorwand, wodurch die Einschnürung energetischer Elektronen weg von dem oberen Abschnitt der Reaktorwand unterstützt wird.

20. Plasmareaktor nach Anspruch 19 bei dem die Quelle (54) eines DC-Magnetfelds in der Nähe eines oberen Abschnitts der Reaktorwand mehrere Permanent-Stabmagneten (54) aufweist, die parallel zueinander und zu einem oberen Abschnitt der Reaktorwand angeordnet sind, wobei der Nordpol von jedem Magneten im wesentlichen senkrecht zu einem oberen Abschnitt der Reaktorwand ausgerichtet ist und der Nordpol im wesentlichen entgegengesetzt von dem von jedem nächsten Nachbarmagnet orientiert ist.

21. Plasmareaktor nach Anspruch 20 weiterhin aufweisend:
eine ferromagnetische Rückschlußplatte (55), die den Magneten (54) wenigstens an der Oberseite bedeckt, und einen ferromagnetischen Rückschluß für die Magnetfeldlinien an den Außenkanten der mehreren Stabmagneten schafft.

22. Plasmareaktor nach Anspruch 19, bei dem die Quelle (54) für ein DC-Magnetfeld in der Nähe eines oberen Abschnitts des Reaktors mehrere konzentrische Ringmagnete parallel zu dem oberen Abschnitt der Reaktorwand aufweist, wobei der Nordpol von jedem Magneten im wesentlichen senkrecht zu dem oberen Abschnitt der Reaktorwand orientiert ist und entgegengesetzt zu dem von jedem Nachbarmagnet ausgerichtet ist, und der eine ferromagnetische Rückschlußplatte (55) aufweist, die die Magnete wenigstens auf der Oberseite bedeckt und einen ferromagnetischen Rückschluß für Magnetfeldlinien an den Außenkanten der mehreren Magnete schafft.

23. Plasmareaktor nach Anspruch 19, bei dem die Quelle (54) des DC-Magnetfelds in der Nähe eines oberen Abschnitts der Reaktorwand einen Scheibenmagneten aufweist, dessen Nordpol im wesentlichen senkrecht zu dem oberen Abschnitt der Reaktorwand ausgerichtet ist.

24. Plasmareaktor nach Anspruch 19, bei dem die Quelle (54) eines DC-Magnetfelds in der Nähe eines oberen Abschnitts der Reaktorwand einen DC-Elektromagneten aufweist, der ein Magnetfeld erzeugt, dessen Nordpol im wesentlichen senkrecht zu dem oberen Abschnitt der Reaktorwand ausgerichtet ist.

25. Plasmareaktor nach Anspruch 19, weiterhin auf-

weisend eine Gleichstromquelle (57) und eine Spule (56), die den Reaktor umgibt und mit der Gleichstromquelle verbunden ist, um ein Gleich-Magnetfeld zu erzeugen, das im wesentlichen senkrecht zu der mit Energie versorgten Elektrode steht.

26. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die mehreren im wesentlichen nicht leitfähigen Spalte symmetrisch bezüglich des Reaktors angeordnet sind.

27. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die unterteilte Faraday-Abschirmung bezüglich der Induktionsspule HF-geerdet ist.

28. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die unterteilte Faraday-Abschirmung bezüglich der Induktionsspule Gleichstrom-geerdet ist.

29. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die unterteilte Faraday-Abschirmung eine gemeinsame Erdung mit der ersten HF-Energiequelle teilt.

30. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die unterteilte Faraday-Abschirmung bezüglich der Induktionsspule geerdet ist.

31. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die Induktionsspule ein Magnetfeld mit einer bestimmten Richtung erzeugt und die durch die unterteilte Faraday-Abschirmung gebildeten Spalte im wesentlichen parallel zu der Richtung des Magnetfelds ausgerichtet sind, so daß die Spalte im wesentlichen die Induzierung eines Stroms in der unterteilten Faraday-Abschirmung durch das Magnetfeld verhindern.

32. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die Induktionsspule ein erstes Ende und ein zweites Ende aufweist, und wobei das erste Ende mit der HF-Energiequelle verbunden ist und das zweite Ende mit einer gemeinsamen Erdung mit der HF-Energiequelle verbunden ist.

33. Plasmareaktor nach Anspruch 32, bei dem der Strom durch die Induktionsspule zwischen dem ersten Ende und einem zweiten Ende so geführt wird, daß die Induktionsspule induktiv Energie von der HF-Energiequelle in das Plasma koppelt.

34. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die unterteilte Faraday-Abschirmung wenigstens zwölf im wesentlichen nicht leitende Spalte bildet, die eine Einkopplung der Energie in das Plasma durch die Induktionsspule ermöglichen.

35. Plasmareaktor nach einem der vorhergehenden Ansprüche, bei dem die Breite der Spalte kleiner ist als der Abstand zwischen Induktionsspule und der Reaktorwand.

36. Plasmareaktor nach Anspruch 35, bei dem die Fläche der unterteilten Faraday-Abschirmung und ein Abstand zwischen der unterteilten Faraday-Abschirmung und dem Plasma so gewählt sind, daß die kapazitive Impedanz zwischen dem Plasma und der unterteilten Faraday-Abschirmung kleiner ist als die kapazitive Impedanz zwischen dem Plasma und jeder HF-Energiequelle.

37. Plasmarektor nach Anspruch 35, weiterhin aufweisend wenigstens eine Quelle für kapazitiv eingekoppelte HF-Energie, wobei die Fläche der unterteilten Faraday-Abschirmung und ein Abstand zwischen der unterteilten Faraday-Abschirmung und dem Plasma so gewählt sind, daß die kapazitive Impedanz zwischen dem Plasma und der unterteilten Faraday-Abschirmung kleiner ist als die kapazitive Impedanz zwischen dem Plasma und der oder jeder kapazitiv eingekoppelten HF-Energiequelle.

38. Plasmareaktor nach Anspruch 37, bei dem die kapazitive Impedanz zwischen dem Plasma und der unterteilten Faraday-Abschirmung um ein mehrfaches geringer ist als die kapazitive Impedanz zwischen dem Plasma und der oder jeder kapazitiv eingekoppelten HF-Energiequelle.

39. Plasmareaktor nach Anspruch 1, weiterhin aufweisend eine Quelle für kapazitiv eingekoppelte Energie für das Plasma, wobei die Quelle für kapazitiv eingekoppelte Energie als eine effektive Kathode bezüglich des Plasmas wirkt, die unterteilte Faraday-Abschirmung als eine effektive Anode bezüglich des Plasmas dient und die Fläche der effektiven Anode größer ist als die Fläche der effektiven Kathode, so daß das Verhältnis C_{s2}/C_{s1} wenigstens 10 beträgt, wobei C_{s2} die Kapazität zwischen dem Plasma und der effektiven Anode und C_{s1} die Kapazität zwischen dem Plasma und der effektiven Kathode ist.

40. Plasmareaktor nach Anspruch 1, bei dem das mittlere Gleichstrompotential des Plasmas nicht größer als 30 Volt bezüglich des Halbleitersubstrats ist.

41. Plasmareaktor nach Anspruch 1, bei dem das Plasma eine Potential-Modulation von nicht mehr als 20 Volt Spitze - Spitze hat.

42. Plasmareaktor nach Anspruch 1, bei dem das Plas-

ma eine Potential-Modulation in der Größenordnung von 20 Volt Spitze - Spitze aufweist.

43. Plasmareaktor nach Anspruch 1, bei dem die Reaktorkammer einen Radius aufweist, die erste HF-Energiequelle eine Frequenz und eine Energie, und der Radius der Reaktorkammer und die Frequenz und die Energie der ersten HF-Energiequelle so gewählt sind, daß ein elektrisches Feld innerhalb der Reaktorkammer mit einer Amplitude Spitze - Spitze in der Größenordnung von 10 V/cm erzeugt wird.

44. Plasmareaktor nach Anspruch 1, bei dem die unterteilte Faraday-Abschirmung geerdet ist.

45. Plasmareaktor nach Anspruch 1, bei dem die im wesentlichen nicht leitenden Spalte eine Breite in der Größenordnung von 1 cm aufweisen.

46. Plasmareaktor nach Anspruch 1, weiterhin aufweisend eine Einrichtung zur Beschleunigung geladener Partikel in Richtung des Halbleiter-Wafers.

47. Plasmareaktor nach Anspruch 1, weiterhin aufweisend eine Einrichtung zur Veränderung der Kapazität zwischen der Abschirmeinrichtung und dem Plasma.

48. Plasmareaktor nach einem der Ansprüche 1 bis 47, bei dem das Halbleitersubstrat eine Oberflächenschicht aus Polysilizium und eine dünne Isolator-Unterschicht aus Siliziumoxid aufweist, die Induktionsspule ausreichend Energie in das Plasma zur Erzeugung einer hohen Ionendichte in dem Plasma einkoppelt und die unterteilte Faraday-Abschirmung im wesentlichen den Wert der Kapazitäts-Modulation verringert, der ohne die unterteilte Faraday-Abschirmung vorliegen würde, so daß die Ionen von dem Plasma in einer kontrollierbaren Weise das Polysilizium mit einer hohen Rate ätzen, ohne im wesentlichen die dünne darunterliegende Oxyd-Isolatorschicht zu beschädigen.

49. Verfahren zur Bearbeitung eines Halbleitersubstrats in einem Plasmareaktor, aufweisend die folgenden Schritte:

Einlaß von Gas in eine Reaktorkammer,
Abschirmung des Gases in der Reaktorkammer mit einer unterteilten Faraday-Abschirmung, wobei die unterteilte Faraday-Abschirmung mehrere im wesentlichen nicht-leitende Spalte zum Durchlaß von induktiv eingekoppelter Energie in das Gas in der Reaktionskammer aufweist,
induktive Einkopplung von Energie in das Gas durch die unterteilte Faraday-Abschirmung, um ein Plasma in der Reaktionskammer zu schaffen,
Bildung von wenigstens einem Plasmaprodukt zur Bearbeitung des Halbleitersubstrats, und
Aussetzen des Halbleitersubstrats zu dem wenigstens einem Plasmaprodukt, um es zu bearbeiten.

50. Verfahren nach Anspruch 49, weiterhin aufweisend den Schritt der Beabstandung der unterteilten Faraday-Abschirmung von dem Plasma.

51. Verfahren nach Anspruch 49, weiterhin aufweisend den Schritt der kapazitiven Einkopplung von Energie in die Reaktionskammer.

52. Verfahren nach Anspruch 49, bei dem der Schritt der Bildung des wenigstens einem Plasmaprodukts weiterhin den Schritt der Bildung eines Plasmas mit einem mittleren Gleichstrompotential von nicht mehr als 30 V bezüglich des Substrats aufweist.

53. Verfahren nach Anspruch 49, bei dem der Schritt der Bildung des wenigstens einem Plasmprodukts weiterhin den Schritt der Bildung eines Plasmas mit einem Potential aufweist, und der Aufrechterhaltung des Potentials des Plasmas so, daß eine Modulation des Plasmapotentials nicht mehr als 20 V Spitze - Spitze beträgt.

54. Verfahren nach Anspruch 49, weiterhin aufweisend die Schritte der Bildung eines Plasmas in der Reaktionskammer, der kapazitiven Einkopplung von Energie in das Plasma durch eine Kapazität C_{s1}, und der kapazitiven Einkopplung von Energie von dem Plasma zu der Erdung durch eine Kapazität C_{s2} zwischen dem Plasma und der unterteilten Faraday-Abschirmung, wobei die Kapazität C_{s1} kleiner ist als die Kapazität C_{s2}.

55. Verfahren nach Anspruch 49, weiterhin aufweisend den Schritt der Veränderung der Kapazität zwischen der unterteilten Faraday-Abschirmung und dem Plasma.

56. Verfahren nach Anspruch 49, weiterhin aufweisend den Schritt der Veränderung der Kapazität zwischen der unterteilten Faraday-Abschirmung und dem Plasma bezüglich der Kapazität zwischen dem Werkstück und dem Plasma.

57. Verfahren nach einem der Ansprüche 49 bis 56, bei dem das Halbleitersubstrat eine Oberflächenschicht aus Polysilizium und eine dünne darunterliegende Oxid-Isolatorschicht aufweist, wobei der Schritt des Aussetzens des Halbleitersubstrats zu dem wenigstens einen Plasmaprodukt weiterhin den Schritt des Ätzens der Oberflächenschicht aus Polysilizium unter Verwendung des wenigstens ei-

nen Plasmaprodukts aufweist, und der Schritt der Abschirmung des Gases weiterhin den Schritt der Steuerung der Energie des wenigstens einen Plasmaprodukts so aufweist, daß die Oberflächenschicht aus Polysilizium geätzt wird, ohne im wesentlichen dünne darunterliegende Oxid-Isolatorschicht zu beschädigen.

Revendications

1. Réacteur à plasma pour le traitement d'un substrat semi-conducteur comprenant:

   une paroi non-conductrice (41) de réacteur entourant une chambre (50) de réacteur dans laquelle un plasma doit être généré pour produire au moins un plasma destiné au traitement du substrat semi-conducteur;
   un moyen destiné à connecter une source (49) de gaz et un système (59) d'échappement de gaz à la chambre de réacteur;
   une bobine d'induction (42) destinée à transférer, par couplage par induction, dans la chambre de réacteur une énergie HF provenant d'une source d'énergie HF;
   une cage de Faraday scindée (46) entre la bobine d'induction et la paroi non-conductrice du réacteur et procurant une pluralité d'intervalles sensiblement non-conducteurs de telle sorte que la source d'énergie HF puisse coupler l'énergie à travers la cage de Faraday scindée pour maintenir ledit plasma; et
   un support destiné au substrat semi-conducteur et positionné de telle sorte que le substrat semi-conducteur soit exposé audit plasma au nombre d'au moins un pendant le traitement.

2. Réacteur à plasma selon la revendication 1, dans lequel la source d'énergie HF comprend une première source (43) d'énergie HF et une deuxième source (51) d'énergie HF.

3. Réacteur à plasma selon la revendication 2, dans lequel la bobine d'induction (42) est couplée à la première source d'énergie HF pour transférer au plasma, par couplage par induction, l'énergie provenant de la première source; et le réacteur comprend, en outre, une électrode (52) couplée à la deuxième source d'énergie haute fréquence (HF) et sur laquelle ou au voisinage de laquelle un substrat semi-conducteur doit être placé pour être traité.

4. Réacteur à plasma selon la revendication 3, dans lequel la bobine d'induction (42) entoure la paroi non-conductrice du réacteur.

5. Réacteur à plasma selon l'une quelconque des revendications 3 et 4, dans lequel l'électrode (52) constitue le support du substrat semi-conducteur couplé à la chambre du réacteur de telle sorte que le substrat semi-conducteur soit exposé au plasma, au nombre d'au moins un, pendant le traitement.

6. Réacteur à plasma selon l'une quelconque des revendication 1 à 3, dans lequel la source d'énergie HF (43) fournit une énergie capacitive et une énergie inductive; et la cage de Faraday scindée est conçue pour empêcher substantiellement l'énergie capacitive provenant de la source d'atteindre la chambre de réacteur tout en permettant à l'énergie inductive provenant de la source d'atteindre la chambre de réacteur.

7. Réacteur à plasma selon la revendication 1, dans lequel ladite cage de Faraday scindée (45) comporte des plaques (46) qui peuvent être déplacée de manière à modifier la capacité entre une masse de plasma se trouvant à l'intérieur de la chambre de réacteur et ladite cage de Faraday scindée.

8. Réacteur à plasma selon la revendication 1, dans lequel ladite cage de Faraday scindée (45) comprend une pluralité de plaques conductrices (46) adjacentes à ladite paroi de réacteur, chaque plaque étant espacée d'une plaque voisine par un intervalle (48) qui est plus petit que la distance entre ladite bobine d'induction et la paroi de réacteur.

9. Réacteur à plasma selon la revendication 1, comprenant, en outre, une électrode alimentée (52) constituant un support au voisinage immédiat duquel doit être placé un substrat semi-conducteur pour être traité, ladite électrode alimentée étant couplée par capacité à la source (43) d'énergie HF.

10. Réacteur à plasma selon la revendication 9, dans lequel ladite bobine d'induction (42) produit, à l'intérieur de la chambre du réacteur, un champ magnétique qui est sensiblement perpendiculaire à ladite électrode alimentée, grâce à quoi un champ électrique, induit dans ladite bobine d'induction par une variation du signal dans le temps, est sensiblement parallèle à ladite électrode alimentée (52) de telle sorte que le champ électrique induit n'affecte pas directement les potentiels du plasma et de l'électrode alimentée.

11. Réacteur à plasma selon la revendication 9, dans lequel ladite source d'énergie HF fournit beaucoup moins d'énergie à l'électrode alimentée (52) que la bobine d'induction, grâce à quoi un plasma produit dans ladite chambre de réacteur présente une densité ionique qui est substantiellement déterminée par l'énergie de ladite bobine d'induction.

12. Réacteur à plasma selon la revendication 11, dans lequel l'énergie fournie à l'électrode alimentée présente une amplitude de tension de crête à crête inférieure à 200 V (volts) de crête à crête, grâce à quoi ce réacteur convient pour une gravure douce d'une plaquette.

13. Réacteur à plasma selon la revendication 9, dans lequel lesdites plaques (46) peuvent être déplacées sur une distance telle que le rapport (C_{s1}/C_{s2}) peut être modifié sur une plage qui comprend la valeur 1, C_{s2} étant la capacité de gaine entre la masse de plasma et la paroi de réacteur et C_{s1} étant la capacité de gaine entre la masse de plasma et l'électrode alimentée.

14. Réacteur à plasma selon la revendication 1, dans lequel la fréquence de l'énergie couplée par induction est f_1 comprise dans la plage allant de 0,1 MHz à 6 MHz.

15. Réacteur à plasma selon la revendication 9, dans lequel l'énergie couplée par induction se trouve à une fréquence f_1 et l'énergie couplée par capacité se trouve à une fréquence f_h qui est au moins deux fois plus grande que l'inverse du temps de transit moyen que prend un ion pour traverser une gaine de plasma au niveau de ladite électrode.

16. réacteur selon la revendication 9, dans lequel l'énergie couplée par capacité se trouve à une fréquence f_h qui est sélectionnée parmi l'ensemble consistant en 13,56 MHz, 27,12 MHz et 40,68 MHz.

17. Réacteur à plasma selon la revendication 1, dans lequel le système d'échappement (59) et la source de gaz (49) produisent, en coopération, à l'intérieur de ladite chambre (50) une pression à laquelle des ions sont créés dans ledit plasma à une vitesse qui est au moins de l'ordre de celle à laquelle sont produits des radicaux libres.

18. Réacteur à plasma selon la revendication 1, comprenant, en outre, une plaque conductrice (53) qui est mise à la masse et qui est adjacente à une partie supérieure de la paroi de réacteur.

19. Réacteur à plasma selon la revendication 1, comprenant, en outre, une source (54) de champ magnétique continu adjacente à une partie supérieure de la paroi de réacteur , ce qui a pour effet de contribuer à maintenir les électrons énergétiques à distance de la partie supérieure de la paroi de réacteur.

20. Réacteur à plasma selon la revendication 19, dans lequel ladite source (54) de champ magnétique continu, adjacente à la partie supérieure de la paroi de réacteur, comprend une pluralité d'aimants permanents en forme de barreaux (54) disposés parallèlement les uns aux autres et à la partie supérieure de la paroi de réacteur, chaque aimant ayant son pôle Nord orienté de façon sensiblement perpendiculaire à la partie supérieure de la paroi de réacteur et ayant son pôle Nord dirigé de façon sensiblement opposée à celle de tous aimants voisins les plus près.

21. Réacteur à plasma selon la revendication 20, comprenant, en outre: une plaque de retour ferromagnétique (55) qui recouvre au moins les aimants (54) sur le dessus et assure un trajet de retour ferromagnétique aux lignes de force magnétiques au niveau des bords extérieurs de la pluralité d'aimants en forme de barreaux.

22. Réacteur à plasma selon la revendication 19, dans lequel ladite source (54) de champ magnétique continu, adjacente à une partie supérieure du réacteur, comprend une pluralité d'aimants annulaires concentriques à la partie supérieure de la paroi de réacteur, chaque aimant ayant son pôle Nord orienté de façon sensiblement perpendiculaire à la partie supérieure de la paroi de réacteur et dirigé de façon opposée par rapport à tous aimants voisins les plus près; et une plaque de retour ferromagnétique (55) qui recouvre au moins les aimants sur le dessus et constitue un trajet de retour ferromagnétique au lignes de force magnétiques au niveau des bords extérieurs de la pluralité d'aimants en forme de barreaux.

23. Réacteur à plasma selon la revendication 19, dans lequel ladite source (54) de champ magnétique continu, adjacente à une partie supérieure de la paroi de réacteur, comprend un aimant en forme de disque ayant son pôle Nord orienté de façon sensiblement perpendiculaire à la partie supérieure de la paroi de réacteur.

24. Réacteur à plasma selon la revendication 19, dans lequel ladite source (54) de champ magnétique continu, adjacente à une partie supérieure de la paroi de réacteur, comprend un électro-aimant à courant continu produisant un champ magnétique ayant son pôle Nord orienté de façon sensiblement perpendiculaire à la partie supérieure de la paroi de réacteur.

25. Réacteur à plasma selon la revendication 19, comprenant, en outre, une source d'énergie en courant continu (57), et une bobine (56) entourant le réacteur et connectée à la source d'énergie en courant continu pour produire un champ magnétique continu qui est sensiblement perpendiculaire à ladite électrode alimentée.

26. Réacteur à plasma selon l'une quelconque des revendications précédentes, dans lequel ladite pluralité d'intervalles sensiblement non-conducteurs est disposée de façon symétrique autour dudit réacteur.

27. Réacteur à plasma selon l'une quelconque des revendications précédentes, dans lequel ladite cage de Faraday scindée est mise à la terre du point de vue HF par rapport à ladite bobine d'induction.

28. Réacteur à plasma selon l'une quelconque des revendications précédentes dans lequel ladite cage de Faraday scindée est mise à la terre du point de vue courant continu par rapport à la dite bobine d'induction.

29. Réacteur à plasma selon l'une quelconque des revendications précédentes, dans lequel ladite cage de Faraday scindée partage une terre commune avec ladite première source d'énergie HF.

30. Réacteur à plasma selon l'une quelconque des revendications précédentes dans lequel ladite cage de Faraday scindée est mise à la terre par rapport à ladite bobine d'induction.

31. Réacteur à plasma selon l'une quelconque des revendications précédentes, dans lequel la bobine d'induction produit un champ magnétique présentant une certaine direction et les intervalles formés par ladite cage de Faraday scindée sont sensiblement parallèles à la direction du champ magnétique de telle sorte que ces intervalles empêchent substantiellement l'induction dans la cage de Faraday scindée d'un courant par ledit champ magnétique.

32. Réacteur à plasma selon l'une quelconque des revendications précédentes dans lequel ladite bobine d'induction comporte une première extrémité et une deuxième extrémité et dans lequel ladite première extrémité est connectée à ladite source d'énergie HF et dans lequel ladite deuxième extrémité est connectée à une terre commune avec ladite source d'énergie HF;

33. Réacteur à plasma selon la revendication 32, dans lequel le courant circule dans ladite bobine d'induction entre ladite première extrémité et une deuxième extrémité de telle sorte que la bobine d'induction transfère par couplage par induction l'énergie de ladite source d'énergie HF audit plasma.

34. Réacteur selon l'une quelconque des revendications précédentes, dans lequel ladite cage de Faraday scindée forme au moins douze intervalles sensiblement non-conducteurs qui permettent à ladite bobine d'induction transfère par couplage l'énergie audit plasma.

35. Réacteur selon l'une quelconque des revendications précédentes, dans lequel la largeur desdits intervalles est plus petite que la distance entre ladite bobine d'induction et la paroi de réacteur.

36. Réacteur à plasma selon la revendication 35, dans lequel la superficie de la cage de Faraday scindée et la distance entre la cage de Faraday scindée et le plasma sont sélectionnées de telle sorte que l'impédance capacitive entre le plasma et la cage de Faraday scindée soient inférieures à l'impédance capacitive entre le plasma et toute source d'énergie HF.

37. Réacteur à plasma selon la revendication 35, comprenant, en outre, au moins une source d'énergie HF couplée par capacité; dans lequel la superficie de la cage de Faraday scindée et la distance entre la cage de Faraday et le plasma sont sélectionnées de telle sorte que l'impédance capacitive entre le plasma et la cage de Faraday scindée soit inférieure à l'impédance capacitive entre le plasma et la source d'énergie HF couplée par capacité ou chaque source d'énergie HF couplée par capacité .

38. Réacteur à plasma selon la revendication 37, dans lequel l'impédance capacitive entre le plasma et la cage de Faraday scindée est plusieurs fois plus petite que l'impédance capacitive entre le plasma et la source d'énergie HF couplée par capacité ou chaque source d'énergie HF couplée par capacité.

39. Réacteur à plasma selon la revendication 1, comprenant, en outre, une source d'énergie couplée par capacité pour ledit plasma, dans lequel la source d'énergie couplée par capacité agit comme une cathode effective vis-à-vis du plasma, la cage de Faraday scindée agit comme une anode effective vis-à-vis du plasma, et la superficie de l'anode effective est beaucoup plus grande que la superficie de la cathode effective de telle sorte que le rapport C_{s2}/C_{s1} soit au moins égal à 10, C_{s2} étant la capacité entre le plasma et l'anode effective et C_{s2} étant la capacité entre le plasma et la cathode effective.

40. Réacteur à plasma selon la revendication 1, dans lequel le potentiel en courant continu moyen du plasma n'est pas supérieur à 30V (volts) par rapport au substrat semi-conducteur.

41. Réacteur à plasma selon la revendication 1, dans lequel le plasma présente une modulation de potentiel qui n'est pas supérieure à 20 V (volts) de crête à crête.

42. Réacteur à plasma selon la revendication 1, dans

lequel le plasma présente une modulation de potentiel de l'ordre de 20 V (volts) de crête à crête.

43. Réacteur à plasma selon la revendication 1, dans lequel la chambre du réacteur présente un certain rayon, la première source d'énergie HF présente une certaine fréquence et une certaine puissance, et le rayon de la chambre du réacteur ainsi que la fréquence et la puissance de la première source d'énergie HF sont sélectionnés de manière à produire dans la chambre du réacteur un champ électrique présentant une amplitude de crête à crête de l'ordre de 10 V/cm(volts/cm).

44. Réacteur à plasma selon la revendication 1, dans lequel la cage de Faraday scindée est mise à la terre.

45. Réacteur à plasma selon la revendication 1, dans lequel chacun des intervalles substantiellement non-conducteurs a une largeur de l'ordre de 1 cm.

46. Réacteur à plasma selon la revendication 1, comprenant, en outre, un moyen pour accélérer des particules chargées vers la plaquette de semi-conducteur.

47. Réacteur à plasma selon la revendication 1, comprenant, en outre, un moyen pour modifier la capacité entre ledit moyen formant cage et le plasma.

48. Réacteur à plasma selon l'une quelconque des revendications 1 à 47, dans lequel le substrat semi-conducteur comprend une couche superficielle de silicium polycristallin et une mince sous-couche isolante en oxyde de silicium, la bobine d'induction transfère par couplage une énergie suffisante dans le plasma pour produire une densité ionique élevée dans ce plasma, et la cage de Faraday scindée réduit substantiellement le niveau de modulation capacitive qui serait présente en l'absence de la cage de Faraday scindée ce qui fait que que les ions provenant du plasma gravent de façon commandable le silicium polycristallin à une vitesse élevée sans endommager sensiblement la mince sous-couche d'oxyde isolant.

49. Procédé de traitement d'un substrat semi-conducteur dans un réacteur à plasma, comprenant les étapes consistant:

à envoyer un gaz dans une chambre de réaction;
à protéger le gaz dans la chambre de réaction avec une cage de Faraday scindée, la cage de Faraday scindée formant une pluralité d'intervalles substantiellement non-conducteurs pour permettre le passage jusque dans la chambre de réaction d'une énergie transférée au gaz par couplage par induction;
à transférer par couplage par induction l'énergie dans le gaz à travers la cage de Faraday scindée pour maintenir un plasma dans la chambre de réaction;
à former au moins un plasma pour traiter le substrat semi-conducteur; et
à exposer le substrat semi-conducteur audit plasma au nombre d'au moins un pour le traiter.

50. Procédé selon la revendication 49, comprenant, en outre, l'étape consistant à ajuster l'espacement de la cage de Faraday vis-à-vis du plasma.

51. Procédé selon la revendication 498, comprenant, en outre l'étape consistant à transférer par couplage par capacité l'énergie dans la chambre de réaction.

52. Procédé selon la revendication 49, dans lequel l'étape consistant à former le plasma au nombre d'au moins un comprend en outre l'étape de formation d'un plasma présentant un potentiel moyen en courant continu qui n'est pas supérieur à 30 V (volts) par rapport au substrat.

53. Procédé selon la revendication 49, dans lequel l'étape consistant à former le plasma au nombre d'au moins un comprend, en outre, les étapes consistant à former un plasma présentant un certain potentiel et à maintenir ce potentiel du plasma de telle sorte qu'une modulation du potentiel du plasma ne soit pas supérieure à 20 V (volts) de crête à crête.

54. Procédé selon la revendication 49, comprenant, en outre, les étapes de formation d'un plasma dans la chambre de réaction, à transférer par couplage par capacité l'énergie dans le plasma par l'intermédiaire d'une capacité C_{s1}, et à transférer par couplage par capacité l'énergie provenant du plasma à la terre par l'intermédiaire d'une capacité C_{s2} entre le plasma et la cage de Faraday scindée, la capacité C_{s1} étant inférieure à la capacité C_{s2}.

55. Procédé selon la revendication 49, comprenant, en outre, l'étape consistant à faire varier la capacité entre la cage de Faraday scindée et le plasma.

56. Procédé selon la revendication 49, comprenant, en outre, l'étape consistant à faire varier la capacité entre la cage de Faraday scindée et le plasma par rapport à la capacité entre la pièce à traiter et le plasma.

57. Procédé selon l'une quelconque des revendications 49 à 56, dans lequel le substrat semi-conducteur

comprend une couche superficielle de silicium polycristallin et une mince sous-couche d'oxyde isolant, l'étape consistant à exposer le substrat semiconducteur audit plasma au nombre d'au moins un comprenant, en outre, l'étape de gravure de la couche superficielle de silicium polycristallin utilisant le plasma au nombre d'au moins un, et l'étape de protection du gaz comprend, en outre, l'étape de commande de l'énergie du plasma au nombre d'au moins un, de telle sorte que la couche superficielle de silicium polycristallin soit gravée sans que soit sensiblement endommagée la mince sous-couche d'oxyde isolant.

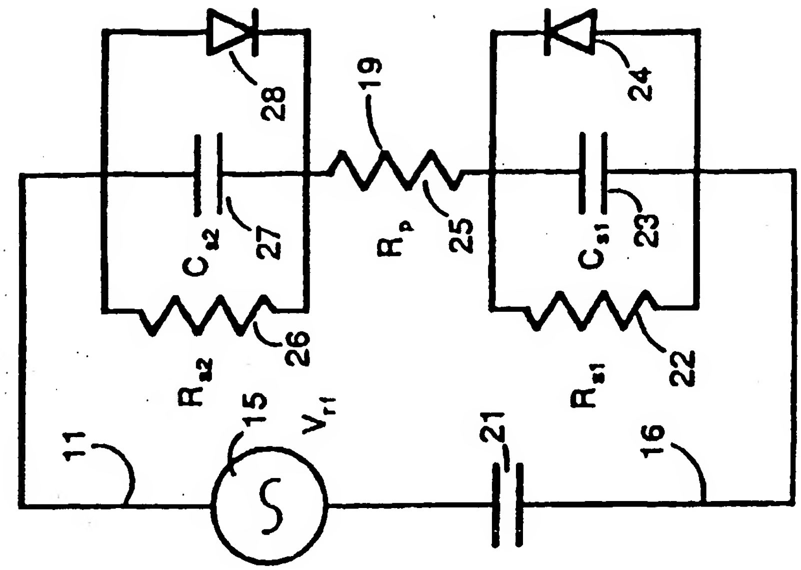

Figure 2 (Prior Art)

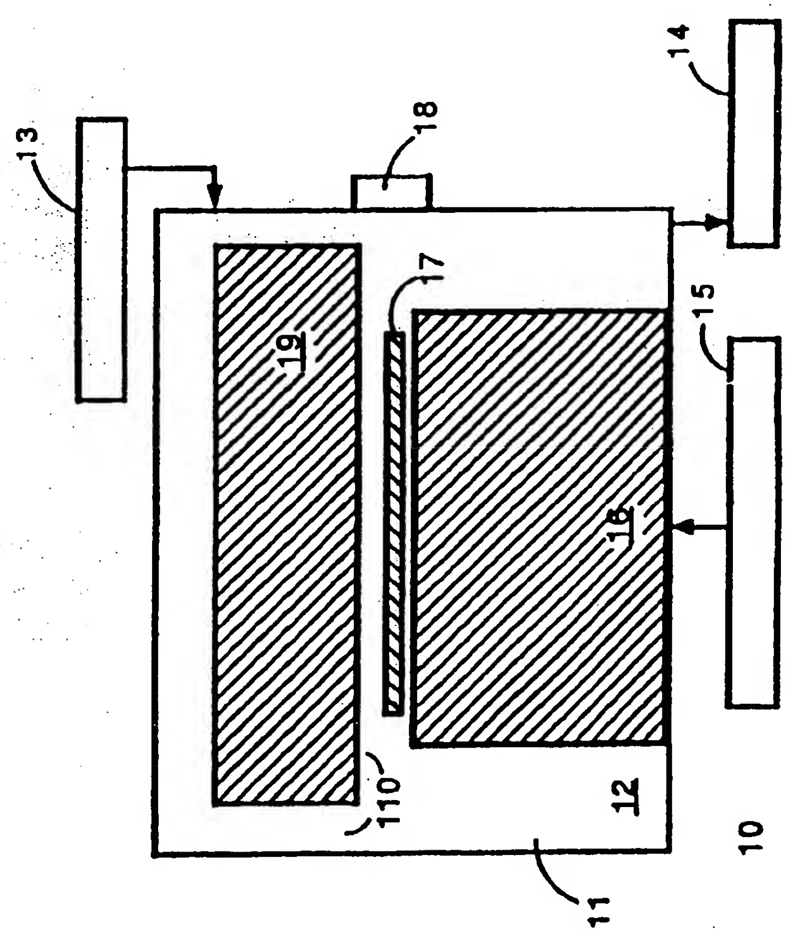

Figure 1 (Prior Art)

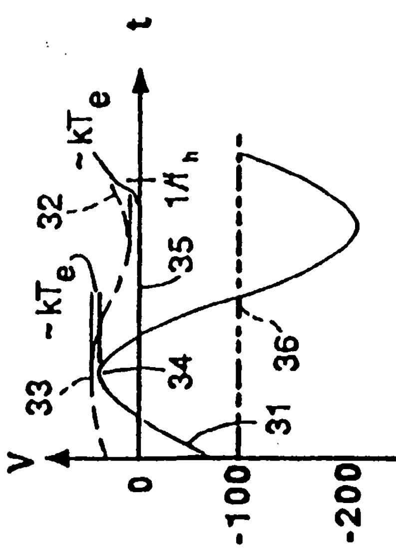

Figure 3

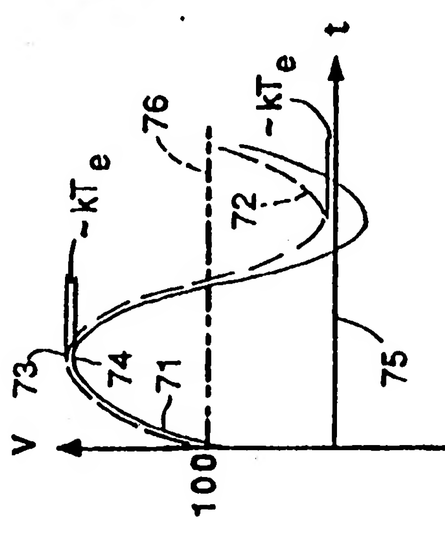

Figure 7

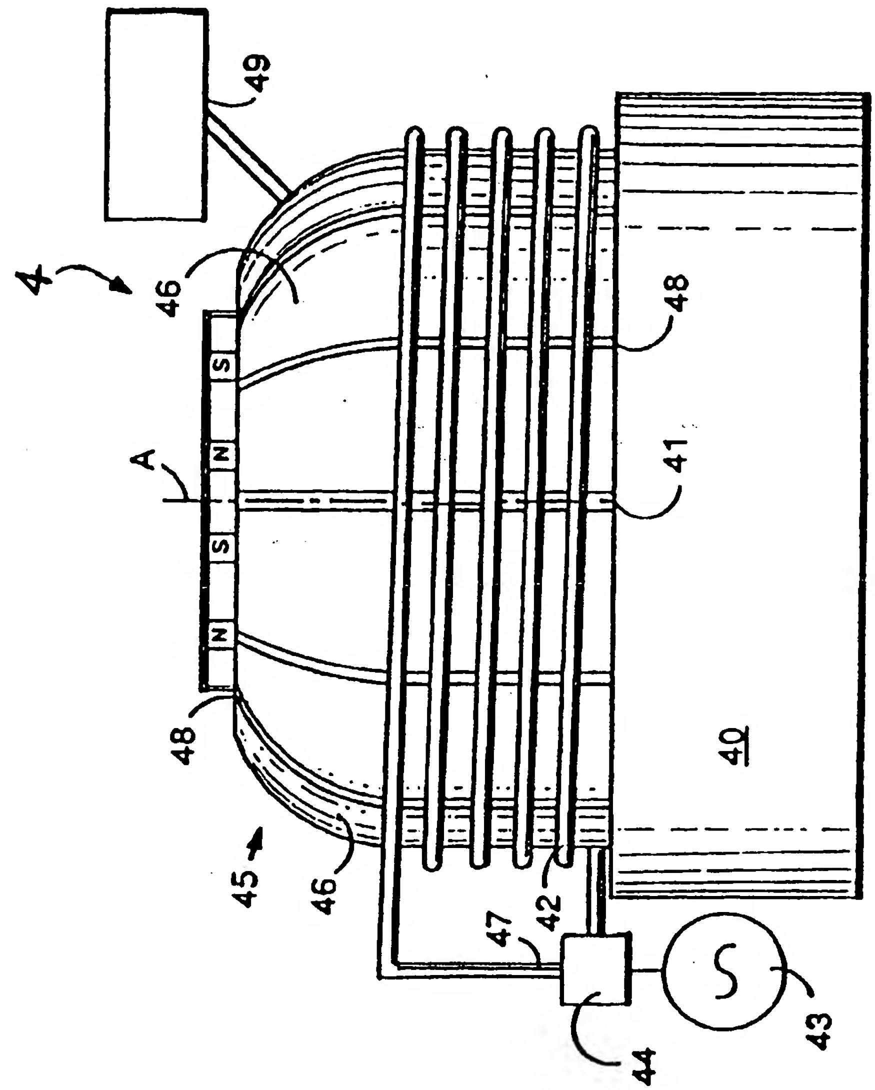

Figure 4

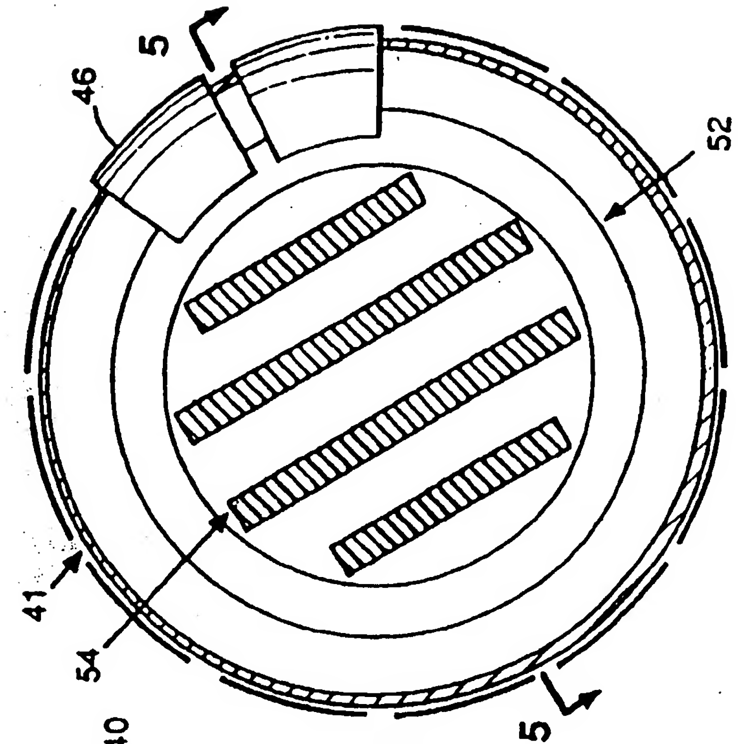

Figure 6

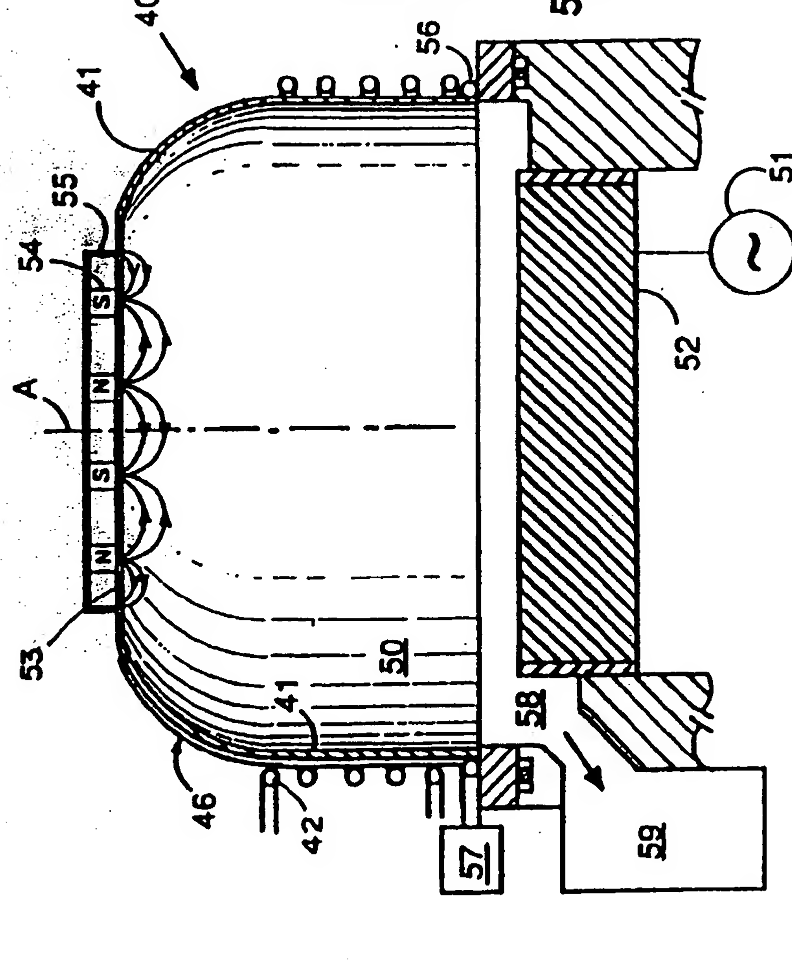

Figure 5

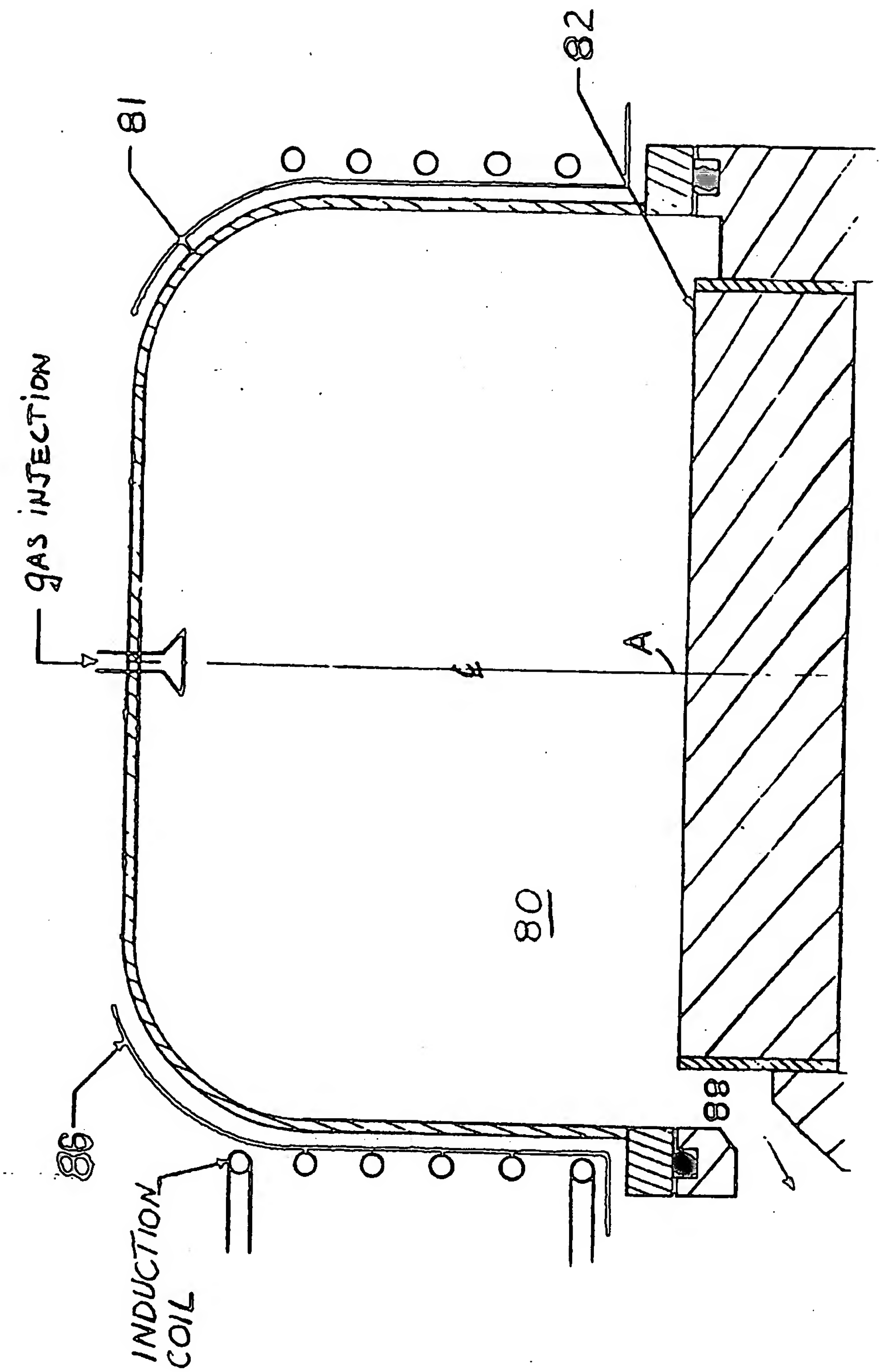

Figure 8